

Austrian Journal of Technical and Natural Sciences

2026, No 5 – 6

Austrian Journal of Technical and Natural Sciences

Scientific journal

№ 5 – 6 2026

ISSN 2310-5607

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Praha 8 – Karlín, Lyčkovo nám. 508/7, PSČ 18600

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SJIF 2024 = 6.62 (Scientific Journal Impact Factor Value for 2024).



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Section 1. Chemistry

DOI:10.29013/AJT-26-5.6-3-8



A NEW CYCLOARTANE TRITERPENE TRIDESMOSIDE FROM ASTRAGALUS MUCIDUS

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Cite: Artikbaeva B.R., Naubeev T.Kh. (2026). A New Cycloartane Triterpene Tridesmoside from *Astragalus mucidus*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-3-8>

Abstract

From the aerial parts of *Astragalus mucidus* (Leguminosae), a new cycloartane glycoside – cycloasidoside C (**1**) – was isolated. Its structure was determined as 3-O-β-D-(3-OAc)-xylopyranoside, 6,25-di-O-β-D-glucopyranoside-24R-cycloartane-3β,6α,16β,24,25-pentol. The structure of the isolated compounds was established based on chemical transformations and ¹H, ¹³C NMR spectra (2D HMBC, HSQC, COSY and DEPT).

Keywords: cycloartane triterpenoids, cycloasidoside C, cycloasgenin C, *Astragalus mucidus*, ¹H and ¹³C NMR

Introduction

Plants and microorganisms remain the most attractive and often uncontested producers of low-molecular bioregulators, also called secondary metabolites. One of the main pathways for the biosynthesis of secondary metabolites is isoprene, which leads to the formation of compounds known as “isoprenoids”. Among natural compounds that have found application in medicine, veterinary and agriculture, isoprenoids occupy a very significant place. It is difficult to overestimate the role of steroid hormones (isoprenoids) in the regulation of the physiological functions of the human body, animals and insects.

In terms of the pace of development, the chemistry of cycloartane-type triterpenoids occupies a very significant place among plant isoprenoids. This class of natural compounds has developed rapidly over the past quarter century and, as a result, the number of compounds with an established structure is approaching a thousand. The source of cycloartane glycosides in our region are plants of the genus *Astragalus* (Leguminosae) (Kaypnazarov T.N., Ramazanov N.Sh., et al. 2020). In the flora of Uzbekistan, this genus is represented by 239 species. We are conducting a selective study of plants of the genus *Astragalus* for isoprenoid content.

Results and discussion

Continuing the study of triterpene glycosides of the cycloartane-type of plants of the genus *Astragalus* (Leguminosae), we investigated the aerial part of *Astragalus mucidus* Bunge for the content of these compounds. The new cycloartane-type glycoside – cycloascidoside C (**1**). Herein the evidence of the structure of these glycosides is provided.

The IR spectrum of compound **1** exhibited absorption bands at 3324 and 2913 cm^{-1} , characteristic of hydroxyl groups and the CH_2 group of a cyclopropane ring, respectively.

In the ^1H NMR spectrum of compound **1**, two one-proton doublets of an AX system were observed at δ 0.18 and 0.54 ppm with a coupling constant of $^2J = 4.2$ Hz, which are characteristic of a 1,1,2,2-tetrasubstituted three-membered ring. In addition, signals corresponding to seven methyl groups appeared at δ 0.97, 1.08, 1.31, 1.39, 1.52, 1.53 and 1.84 ppm. Furthermore, four signals of methine protons at δ 3.44 (dd, $J = 11.6, 4.4$ Hz), 3.67 (dd, $J = 10.6, 2.4$ Hz), 3.69 (td, $J = 9.2, 3.8$ Hz), and 4.66 (td, $^3J_1 = ^3J_2 = 7.8$ Hz, $^3J_3 = 5.4$ Hz) indicated the presence of secondary alcohol functionalities.

The carbon atoms of the cyclopropane ring, C-9, C-10, and C-19, resonated in the ^{13}C NMR spectrum at δ 21.94, 28.87, and 30.41 ppm, respectively. These data allowed us to classify compound **1** as a cycloartane-type triterpenoid (Gvazava L. N. and Kikoladze V.S., 2012; Shameem S.A., Banday A.H., et al., 2022; Aslanipour B., Gülcemal D., et al. 2017).

The ^1H NMR spectrum of compound **1** also showed a three-proton singlet at δ 2.05 ppm, indicating the presence of a single acetate group in the glycoside molecule. As expected, the ^{13}C NMR spectrum of the new glycoside **1** displayed signals at δ 21.71 and 170.57 ppm, corresponding to the carbon atoms of the acetyl moiety.

Acid hydrolysis of compound **1** yielded cycloasgenin C (Figure 1) as the aglycone (Kucherbaev K.Dzh., Uteniyazov K. K., Kachala V. V., et al., 2002; Isaev M. I., Gorovits M. B., et al., 1982). In addition, paper chromatography of the hydrolysate, followed by comparison with authentic standards, revealed the presence of D-glucose and D-xylose.

Alkaline hydrolysis of cycloascidoside C (**1**) resulted in the formation of glycoside **3**,

which was identified as cycloascidoside E (**3**) (Figure 1). Therefore, cycloascidoside C (**1**) can be regarded as a monoacetyl derivative of cycloascidoside E (**3**) (Naubeev T. X., Janibekov A. A., Kucherbaev K.Dzh., 2017).

The position of the acetyl group attachment was established through a comparative analysis of the ^1H and ^{13}C NMR spectra of compounds **1** and **3**.

As shown in table 1, the transition from glycoside **1** to glycoside **3** is accompanied by significant changes in the chemical shifts of the carbon atoms C-2 (-3.27 ppm), C-3 ($+1.15$ ppm), and C-4 (-1.89 ppm) of the xylopyranosyl residue.

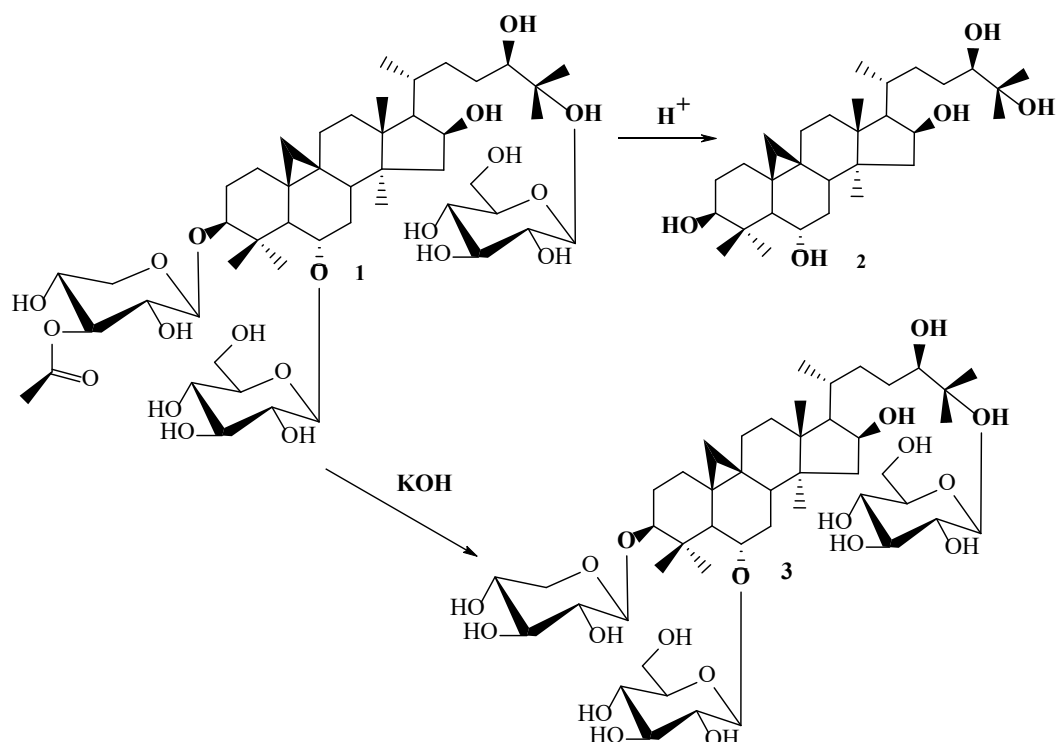
Comparison of the ^{13}C NMR signals of the anomeric carbon atoms in compound **1** and cycloascidoside E (**3**) confirmed the location of the acetyl group at the C-3 position of the xylopyranose residue (Table 1).

The signals of the anomeric carbon atom of the xylopyranosyl residue attached to the aglycone at C-3 appear at δ 108.16 and 107.62 ppm in the ^{13}C NMR spectra of cycloascidoside C (**1**) and cycloascidoside E (**3**), respectively. The chemical shifts of the anomeric carbon atoms remained essentially unchanged. Comparison of the carbon chemical shifts for cycloascidoside C (**1**) and cycloascidoside E (**3**) showed that, in the former, the signal of carbon C-2' of the xylose residue experienced an upfield shift of 3.27 ppm, confirming the presence of an acetyl substituent within the xylose moiety. The magnitude of this upfield shift indicates that the acetyl group is located on the adjacent carbon atom, C-3'.

This conclusion is further supported by the upfield shift of the C-3' signal by 1.15 ppm. In the ^1H NMR spectrum of cycloascidoside C (**1**), the proton geminal to the acetylated carbon resonates as a triplet at δ 5.58 ppm with coupling constants of $^3J_1 = ^3J_2 = 8.7$ Hz.

Based on these data, we concluded that the acetyl group in cycloascidoside C (**1**) is attached to the C-3' position of the xylose residue.

In the anomeric proton region of the ^1H NMR spectrum of cycloascidoside C (**1**), three signals were observed at δ 4.80 ppm (H-1, d, β -D-Xylp), δ 4.97 ppm (H-1', d, β -D-Glcp), and δ 5.23 ppm (H-1'', d, β -D-Glcp). The coupling constants of the anomeric protons were $^3J = 7.9, 7.7, \text{ and } 7.8$ Hz, respectively, indicating the β -configuration of all sugar residues.

Figure 1. Acidic and alkaline hydrolysis of cycloascidoside C (1)

In the ^{13}C NMR spectrum of cycloasgenin C (2), the signals corresponding to carbon atoms C-3, C-6, and C-25 were observed at δ 78.39, 68.33, and 72.74 ppm, respectively.

In the spectrum of cycloascidoside C (1), the corresponding carbon signals appeared at δ 89.41, 79.68, and 81.38 ppm (Table 1).

Table 1. ^{13}C NMR spectral data of cycloascidoside C (1), aglycone 2 and cycloascidoside E (3) ($\text{C}_5\text{D}_5\text{N}$, δ , ppm, J/Hz, TMS as internal standard)

Atom C	DEPT	1	2	3	Atom C	DEPT	1	2	3
1	CH_2	32.53	32.83	32.20	27	CH_3	24.74	26.19	24.22
2	CH_2	29.68	31.51	30.22	28	CH_3	20.34	20.34	19.83
3	CH	89.41	78.39	88.55	29	CH_3	28.73	29.41	28.52
4	C	42.75	42.51	42.65	30	CH_3	17.04	16.22	16.63
5	CH	52.96	54.05	52.48	3-O-β-D-Xylp				
6	CH	79.68	68.33	79.16	1	CH	108.16		107.62
7	CH_2	34.92	38.69	34.23	2	CH	72.31		75.58
8	CH	46.18	47.28	45.62	3	CH	79.65		78.50
9	C	21.94	21.33	21.38	4	CH	69.33		71.22
10	C	28.87	29.62	28.71	5	CH_2	67.59		67.02
11	CH_2	26.70	26.42	26.26	Ac		21.71		
12	CH_2	33.59	33.22	33.14	Ac		170.57		
13	C	46.25	45.76	45.66	6-O-β-D-Glcp'				
14	C	47.38	47.00	46.89	1	CH	105.63		105.13
15	CH_2	48.66	48.86	48.05	2	CH	75.87		75.58
16	CH	72.13	71.76	71.75	3	CH	79.45		79.16
17	CH	57.65	57.28	57.15	4	CH	71.81		71.75

Atom C	DEPT	1	2	3	Atom C	DEPT	1	2	3
18	CH ₃	19.08	18.84	18.47	5	CH	78.66		78.09
19	CH ₂	30.42	30.40	30.33	6	CH ₂	63.57		63.08
20	CH	32.06	31.68	31.55	25-O-β-D-Glcp"				
21	CH ₃	19.31	19.16	18.80	1	CH	99.21		98.69
22	CH ₂	35.40	34.90	34.96	2	CH	76.11		75.35
23	CH ₂	29.16	29.44	29.25	3	CH	79.04		78.71
24	CH	78.74	80.65	78.94	4	CH	72.24		71.77
25	C	81.38	72.74	80.56	5	CH	79.24		78.20
26	CH ₃	22.02	26.03	21.50	6	CH ₂	63.23		62.74

Therefore, glycosylation effects were observed only for carbon atoms C-3 (+11.24 ppm), C-6 (+11.35 ppm), and C-25 (+8.64 ppm), whereas the chemical shifts of carbon atoms C-16 and C-24 remained essentially unchanged.

The ¹³C NMR spectrum of cycloascidoside C (**1**) exhibited signals of three anomeric carbon atoms resonating at δ 108.16, 105.63, and 99.21 ppm, respectively. These data indicate that the D-xylose residue is attached at C-3 of the aglycone, while two D-glucose residues are linked at C-6 and C-25.

In the ¹³C NMR spectrum of cycloascidoside C (**1**), three signals were observed in the region characteristic of anomeric carbon atoms, indicating that the compound is a triglycoside. Analysis of the COSY and TOCSY spectra allowed the identification of distinct spin systems corresponding to the sugar residues and enabled determination of the monosaccharide composition of the carbohydrate moiety based on chemical shift values and coupling constants.

These assumptions were further confirmed by HMBC correlations between H-1 of the xylose residue (δ 4.80 ppm) and C-3 of the aglycone (δ 89.41 ppm), H-1 of a glucose residue (δ 4.97 ppm) and C-6 of the aglycone (δ 79.68 ppm), and H-1 of the second glucose residue (δ 5.23 ppm) and C-25 of the aglycone (δ 81.38 ppm). Additionally, an HMBC correlation was observed between H-3' of the xylose residue (δ 5.58 ppm) and the acetyl carbonyl carbon (δ 170.57 ppm), providing conclusive evidence for the positions of the sugar residues and the acetyl group.

Based on the obtained experimental data, the new cycloartane glycoside, cycloascidoside C (**1**), was identified as

24R-cycloartane-3β,6α,16β,24,25-pentaol 3-O-β-D-(3-O-acetyl)-xylopyranoside, 6,25-di-O-β-D-glucopyranoside.

Isolation and purification of isoprenoids from the aerial parts of *Astragalus mucidus* Bunge were carried out as previously described (Naubeev T. Kh., Uteniyazov K. K., Isaev M. I., 2011). The aerial parts of *Astragalus mucidus* (1.5 kg), collected in the Namangan region of the Republic of Uzbekistan, were air-dried and finely ground. The plant material was extracted five times with 8 l portions of methanol. The combined methanolic extracts were concentrated under reduced pressure using a rotary evaporator at 40–50 °C to a syrup-like consistency and then mixed with twice their volume of water. The resulting aqueous residue was successively extracted with chloroform and then with *n*-butanol. The *n*-butanol extract was evaporated to dryness under reduced pressure.

A total of 75 g of the dry *n*-butanol residue was subjected to column chromatography on silica gel. Elution with a chloroform-methanol-water solvent system (70:23:3) afforded 150 mg of cycloascidoside C (**1**), corresponding to a yield of 0.01% based on the air-dried plant material.

Cycloascidoside C (1**)**, C₄₉H₈₂O₂₀, white amorphous powder, mp 292–294 °C (from CH₃OH).

¹H NMR spectrum of cycloascidoside C (600 MHz, C₅D₅N, δ ppm, J/Hz, TMS as internal standard): δ 0.18 and 0.54 (each d, J = 4.2 Hz, 2H, H-19), 0.97 (s, CH₃-28), 1.08 (3H, d, J = 6.4 Hz, CH₃-21), 1.31, 1.39, 1.52, 1.53, and 1.84 (each s, 5 × CH₃), 2.05 (3H, s, OAc), 3.44 (1H, dd, J=11.6, 4.4, H-3), 3.56 (1H, dd, J=10.5, 2.5, H-5a, β-D-Xylp), 3.67

(dd, $J=10.6, 2.4$, H-24), 3.69 (1H, td, $J=9.2, 3.8$, H-6), 3.82 (1H, m, H-5'', Glcp), 3.90 (1H, dd, $J=8.4, 7.8$, H-2'', Glcp), 3.92 (1H, dd, $J=8.9, 7.8$, H-2', Glcp), 3.94 (ddd, $J=9.2, 5.1, 2.7$, H-5', Glcp), 4.04 (1H, dd, $J=8.8, 7.8$, H-2, Xylp), 4.07 (1H, t, $J=8.9$, H-4', Glcp), 4.08 (1H, t, $J=8.5$, H-4', Glcp), 4.09 (1H, t, $J=8.8$, H-3', Glcp), 4.16 (1H, t, $J=8.8$, H-3'', Glcp), 4.17 (1H, dd, $J=11.3, 5.4$, H-6'', Glcp), 4.21 (1H, dd, $J=11.7, 5.5$, H-6', Glcp), 4.34 (1H, dd, $J=11.5, 5.2$, H-5e, Xylp), 4.35 (1H, dd, $J=11.7, 5.1$, H-6', Glcp), 4.49 (1H, td, $J=7.5, 7.6, 4.8$, H-4, Xylp), 4.56 (1H, dd, $J=11.8, 3$, H-6'', Glcp), 4.66 (td, $J=7.8, 5.4$, H-16), 4.80 (1H, d, $J=7.9$, H-1, Xylp), 4.97 (1H, d, $J=7.7$, H-1', Glcp), 5.23 (1H, d, $J=7.8$, Glcp, H-1''), 5.58 (1H, t, $J=8.7$, H-3, Xylp).

The ^{13}C NMR spectral data of cycloascidoside C are presented in Table 1.

Acid hydrolysis of Cycloascidoside C. Glycoside **1** (50 mg) was dissolved in 20 mL of 50% aqueous methanol containing 0.5% sulfuric acid, and the solution was refluxed for 1 h. After completion of the reaction, water was added, the methanol was removed under reduced pressure, and the reaction products were extracted with *n*-butanol. The butanolic extract was washed with water and evaporated to dryness.

Subsequent column chromatography using solvent system chloroform-methanol (25:1) afforded 10 mg of cycloasgenin C (**2**) as a white amorphous powder, $\text{C}_{30}\text{H}_{52}\text{O}_5$, mp 250–252 °C (from acetone).

Paper chromatography (PC) in solvent system *n*-butanol-pyridine-water (6:4:3) revealed the presence of D-glucose and D-xylose in the hydrolysate.

^1H NMR spectrum of cycloasgenin C (600 MHz, $\text{C}_5\text{D}_5\text{N}$, δ ppm, J/Hz, TMS as internal standard): δ 0.35 and 0.62 (d, $J = 4.0$ Hz, 2H, H-19), 1.06 (s, CH_3), 1.13 (d, $J = 6.4$ Hz, CH_3 –21), 1.40, 1.45, 1.52, 1.54 and 1.93 (each s, $5 \times \text{CH}_3$), 3.69 (dd, $J = 11.4$ Hz, H-3), 3.71 (dd, $J = 10.3, 2.3$ Hz, H-24), 3.82 (td, $J = 9.3, 3.7$ Hz, H-6) and 4.75 (td, $J = 7.7, 4.9$ Hz, H-16).

The ^{13}C NMR spectral data of cycloasgenin C are presented in Table 1.

Alkaline hydrolysis of Cycloascidoside C. Cycloascidoside C (**1**) (50 mg) was dissolved in 20 mL of a 0.5% methanolic KOH solution. The reaction mixture was kept at 25 °C for 24 h. The solution was then diluted with 35 mL of water, neutralized with acetic acid, and the methanol was removed under reduced pressure. The reaction products were extracted with *n*-butanol, after which the solvent was evaporated.

Chromatographic separation using solvent system chloroform-methanol-water (70:23:3) yielded 12 mg of cycloascidoside E (**3**), $\text{C}_{47}\text{H}_{80}\text{O}_{19}$, mp 276–278 °C (from CH_3OH).

Cycloascidoside E (3), $\text{C}_{47}\text{H}_{80}\text{O}_{19}$, white amorphous powder, mp 276–278 °C (from methanol).

^1H NMR spectrum of cycloascidoside E (600 MHz, $\text{C}_5\text{D}_5\text{N}$, δ ppm, J/Hz): δ 0.20 and 0.59 (each ^1H , d, $J = 4.2$ Hz, H-19), 0.83 (3H, s, Me-28) and 1.08 (3H, d, $J = 6.6$ Hz, Me-21), 1.38, 1.39, 1.52, 1.53, 2.06 (3H, s, Me-30, Me-18, Me-27, Me-26, Me-29), 3.56 (1H, dd, $J=11.6, 4.4$, H-3), 3.71 (1H, dd, $J=11.3, 10$, H-5 α Xylp), 3.83 (1H, td, $J=8.4, 4.2$, H-6), 3.85 (1H, m, Glcp H''-5), 3.92 (1H, ddd, $J=8.2, 5.7, 2.5$, Glcp H-5'), 3.93 (1H, dd, $J_1=8.3, 8$, Glcp H'-2), 3.91 (1H, dd, $J=8.6, 7.5$, Glcp H-2''), 3.93 (1H, dd, $J=8.6, 7.5$, Xylp H-2), 4.01 (1H, t, $J=8.2$, Xylp H-3), 4.09 (1H, m, Xylp H-4), 4.06 (1H, t, $J=8.7$, Glcp H-4'), 4.07 (1H, t, $J=8.6$, Glcp H-4''), 4.08 (1H, t, $J=8.7$, Glcp H-3'), 4.17 (1H, t, $J=9$, Glcp H-3''), 4.22 (1H, dd, $J=11.5, 5.1$, Xylp H-5e), 4.25 (1H, dd, $J=11.5, 5.5$, Glcp H-6''), 4.26 (1H, dd, $J=11.6, 5.4$, Glcp H-6'), 4.36 (1H, dd, $J=11.6, 5.1$, Glcp H-6), 4.56 (1H, dd, $J=11.8, 2.6$, Glcp H-6''), 4.67 (1H, td, $J=7.3, 6.5$, H-16), 4.86 (1H, d, $J=7.5$, Xylp H-1), 4.94 (1H, d, $J=7.7$, Glcp H-1'), 5.24 (1H, d, $J=7.8$, Glcp H-1'').

The ^{13}C NMR spectral data of cycloascidoside E (**3**) are presented in Table 1.

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submitted 15.06.2026;
accepted for publication 29.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-9-16



SYNTHESIS AND SPECTROSCOPIC CHARACTERIZATION OF POLYETHYLENEPOLYAMINE-MODIFIED POLYACRYLONITRILE (PPA) FIBER FOR FUTURE METAL-ION ANALYSIS

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Cite: Avazyazov M., Ashirov M. (2026). *Synthesis and Spectroscopic Characterization of Polyethylenepolyamine-Modified Polyacrylonitrile (PPA) Fiber for Future Metal-Ion Analysis. Austrian Journal of Technical and Natural Sciences 2026, No 5–6.* <https://doi.org/10.29013/AJT-26-5.6-9-16>

Abstract

Polyacrylonitrile (PAN) fiber was sequentially modified through alkaline hydrolysis, amination/amidoximation with hydroxylamine hydrochloride and hydrazinium chloride, grafting with polyethylenepolyamine (PEPA), and acid activation to produce a chemically functionalized PPA fiber suitable as a solid support for reagent immobilization. Ferron (7-iodo-8-hydroxyquinoline-5-sulfonic acid), a well-established chromogenic reagent for Fe(III), Fe(II), and Al(III) ions, was subsequently immobilized onto the PPA fiber by equilibrium sorption from a 0.0057 M aqueous solution at 25 °C for 24 h. The parent PAN, synthesized PPA, and Ferron-immobilized PPA fibers were characterized by Fourier-transform infrared (FTIR) spectroscopy and diffuse reflectance spectroscopy (DRS) using an EFI ES-2000 color calibrator spectrophotometer. FTIR analysis confirmed the partial conversion of nitrile groups (2241 cm^{-1}) into amide, amidoxime, and amine-related functionalities, with progressive spectral changes upon each modification step. Immobilization of Ferron introduced additional absorption bands consistent with aromatic and sulfonate functional groups. DRS measurements revealed a pronounced optical response in the 380–520 nm region for the Ferron-immobilized fiber, distinct from the unmodified PPA spectrum. These results establish that PPA fiber effectively retains Ferron on its surface and that the immobilized reagent retains its chromogenic functionality, providing a spectroscopic basis for the future development of a solid-phase colorimetric sensor for the qualitative and quantitative determination of Fe(III), Fe(II), and Al(III) ions in wastewater samples.

Keywords: polyacrylonitrile fiber; PEPA grafting; Ferron immobilization; FTIR spectroscopy; diffuse reflectance spectroscopy; 7-iodo-8-hydroxyquinoline-5-sulfonic acid; metal-ion detection; solid-phase sensor; wastewater analysis

1. Introduction

Heavy metal pollution of water resources is a pressing environmental concern worldwide. Iron and aluminum ions, while

naturally abundant, can reach elevated concentrations in industrial effluents, mining drainage, and municipal wastewater, posing risks to aquatic ecosystems and human

health (Deng S., Bai R., and Chen J. P., 2003; Burakov A. E., Galunin E. V., Burakova I. V., et al., 2018). The development of simple, rapid, and cost-effective analytical methods for monitoring these ions is therefore of considerable practical importance.

Spectrophotometric methods based on chromogenic reagents offer a well-established approach for metal-ion detection. Among the available reagents, 7-iodo-8-hydroxyquinoline-5-sulfonic acid, commonly known as Ferron, has been widely used for the colorimetric determination of Fe(III), Fe(II), and Al(III) owing to its ability to form stable, intensely colored complexes with these ions (Cheng K. L., Ueno K., and Imamura T., 1992; Moldovan Z. and Neagu E. A., 2002). The selectivity and sensitivity of Ferron-based methods have led to their application in diverse matrices, including natural waters, soils, and biological fluids (Parker D. R. and Bertsch P. M., 1992; Goto K., Tamura H., Onodera M., and Nagayama M., 1974).

In solution-phase colorimetry, the reagent is consumed in a single measurement, generating chemical waste and requiring frequent reagent preparation. Immobilization of chromogenic reagents on solid supports addresses these limitations by enabling reagent reuse, simplifying separation from the sample matrix, and facilitating integration into solid-phase sensing platforms (Ruvubu S. B. and Roy I., 2026; Rahman I. M. M., Begum Z. A., and Hasegawa H., 2013). The choice of support material is critical: it must provide abundant surface functional groups for reagent attachment, exhibit chemical and mechanical stability, and permit optical interrogation of the immobilized reagent.

Polyacrylonitrile (PAN) fiber is an attractive candidate for this purpose. PAN is produced on an industrial scale, possesses good mechanical properties, and contains nitrile groups that can be chemically transformed into a variety of functional moieties (Bashir Z., 1991; Shin D. H., Ko Y. G., Choi U. S., and Kim W. N., 2004). Alkaline hydrolysis converts a portion of the nitrile groups to carboxylate and amide functionalities, increasing hydrophilicity and providing anchoring points for further modification. Subsequent amination with hydroxylamine hydrochloride introduces amidoxime groups, which are known for their

metal-chelating ability (Saeed K., Haider S., Oh T.-J., and Park S.-Y., 2008; Huang F., Xu Y., Liao S., Yang D., Hsieh Y.-L., and Wei Q., 2013). Grafting with polyethylenepolyamine (PEPA) further increases the density of amine-containing binding sites, creating a highly functionalized surface (Shahidova D. and Gafurova D., 2024).

In this study, we report the sequential synthesis of a PEPA-modified PAN (PPA) fiber and its use as a support for the immobilization of Ferron. The chemical transformations at each stage were monitored by FTIR spectroscopy, and the optical properties of the Ferron-immobilized fiber were characterized by diffuse reflectance spectroscopy (DRS). The overall objective is to establish the spectroscopic basis for a subsequent application in which the Ferron-PPA fiber is employed for the qualitative and quantitative determination of Fe(III), Fe(II), and Al(III) ions in wastewater samples using color change analysis with a calibrated DRS instrument.

2. Materials and Methods

2.1 Materials

Polyacrylonitrile (PAN) fiber was used as the base polymer. Sodium hydroxide (NaOH), hydroxylamine hydrochloride (CAS 5470–11–1), hydrazinium chloride (CAS 2644–70–4), dimethylformamide (DMF), polyethylenepolyamine (PEPA, 50% w/w aqueous solution), hydrochloric acid (HCl), and Ferron (7-iodo-8-hydroxyquinoline-5-sulfonic acid, CAS 547–91–1) were used as received. All solutions were prepared with bidistilled water.

2.2 Synthesis of PPA Fiber

The synthesis followed a four-step route: alkaline hydrolysis of PAN, amination/amidoximation, PEPA grafting, and acid activation. A 2.0 g portion of PAN fiber was first treated with 80 mL of 1 M NaOH at a bath ratio of 1:40 for 60 min at 90 °C. This treatment was intended to increase hydrophilicity and generate carboxylate and amide sites from a portion of the nitrile groups. The hydrolyzed fiber was washed five times with bidistilled water and dried at ambient temperature.

The hydrolyzed fiber was then aminated in 100 mL of reaction solution containing 6.0 g hydroxylamine hydrochloride, 0.7 g hydrazinium chloride, and 5.0 mL DMF. The pH

was adjusted to 8.0–8.5 with 1 M NaOH to form the active nucleophilic species. The reaction was maintained at 90 °C for 1.5 h with continuous stirring. Hydrazinium chloride was used in place of hydrazine hydrate to improve handling safety and storage stability while preserving the intended cross-linking function. After reaction, the fiber was washed five times with bidistilled water and dried at ambient temperature.

For PEPA grafting, the aminated fiber was immersed in 80 mL of 50% (w/w) PEPA solution at a bath ratio of 1:40. The reaction was conducted at 100 °C for 5 h under continuous stirring. The elevated temperature and ex-

tended reaction time were selected to support diffusion of PEPA into the fiber matrix and to increase the density of amine-containing binding sites. The obtained PPA fiber was washed exhaustively five times with bidistilled water and dried at ambient temperature.

Before Ferron immobilization, the dried PPA fiber was activated in 0.1 M HCl at a bath ratio of 1:75 for 24 h at 25 °C. For a 2.0 g fiber sample, 150 mL of acid solution was used. This step protonates amine groups and removes weakly retained oligomeric residues. The activated PPA fiber was washed with bidistilled water and dried at ambient temperature.

Table 1. Summary of experimental conditions for each stage of PPA fiber synthesis and Ferron immobilization

Stage	Experimental Conditions
Alkaline hydrolysis	PAN fiber (2.0 g); 80 mL of 1 M NaOH; bath ratio 1:40; 90 °C; 60 min; washed 5×, dried
Amination	Hydrolyzed fiber in 100 mL medium; 6.0 g $\text{NH}_2\text{OH}\cdot\text{HCl}$, 0.7 g $\text{N}_2\text{H}_4\cdot 2\text{HCl}$, 5.0 mL DMF; pH 8.0–8.5; 90 °C; 1.5 h
PEPA grafting	Aminated fiber in 80 mL of 50% (w/w) PEPA; bath ratio 1:40; 100 °C; 5 h; washed, dried
Acid activation	Dried PPA fiber in 0.1 M HCl; bath ratio 1:75; 24 h at 25 °C; washed, dried
Ferron immobilization	PPA fiber in 20 mL of 0.0057 M Ferron; 24 h at 25 °C; characterized spectroscopically

2.3 Ferron Immobilization

Ferron was immobilized by immersing the activated PPA fiber in 20 mL of 0.0057 M Ferron solution for 24 h at 25 °C. After immobilization, the fiber was removed from the solution, rinsed briefly with bidistilled water to remove non-adsorbed reagent, and dried at ambient temperature prior to spectroscopic characterization.

2.4 Instrumental Characterization

Fourier-transform infrared (FTIR) spectra of the parent PAN fiber, synthesized PPA fiber, and Ferron-immobilized PPA fiber were recorded using a Shimadzu IRTracer-100 FTIR spectrophotometer in the wavenumber range 400–4000 cm^{-1} . Diffuse reflectance spectra (DRS) of PPA and Ferron-immobilized PPA fibers were obtained with an EFI ES-2000 color calibrator spectrophotometer to monitor the

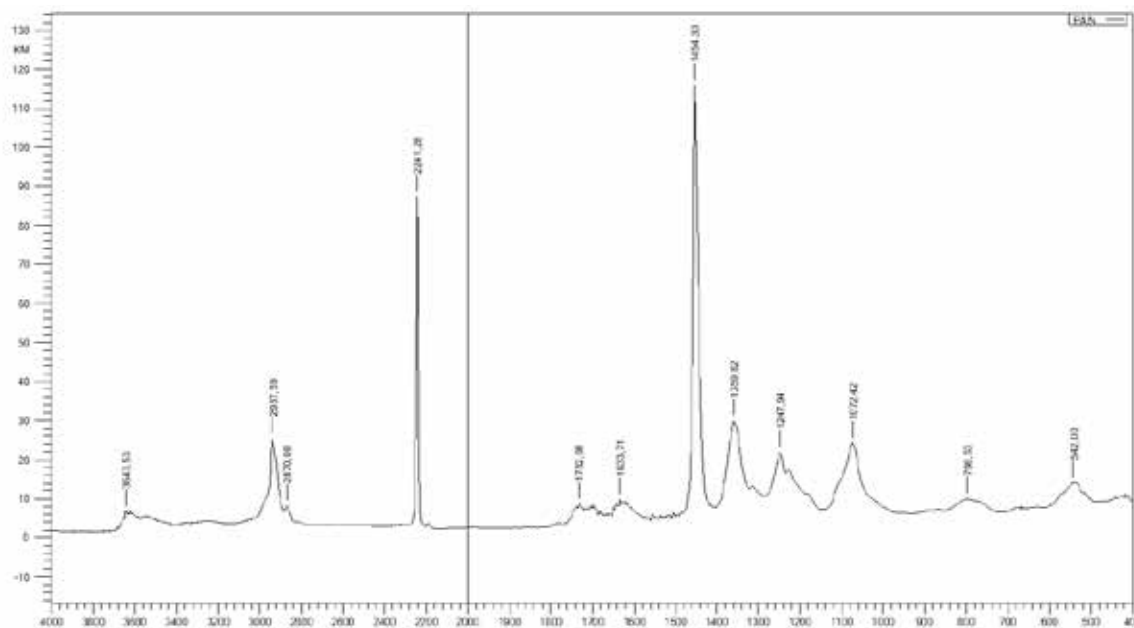
optical change produced by Ferron immobilization.

3. Results and Discussion

3.1 FTIR Analysis of PAN Fiber

The FTIR spectrum of the initial PAN fiber is presented in (Figure 1). The characteristic nitrile ($\text{C}\equiv\text{N}$) stretching vibration was observed at 2241 cm^{-1} , together with aliphatic C–H stretching bands near 2938 and 2870 cm^{-1} . Additional bands appeared at 1454, 1359, 1248, 1072, 799, and 542 cm^{-1} , corresponding to the polymer backbone and various bending and vibrational modes of the unmodified PAN matrix (Bajaj P., Sreeku-mar T. V., and Sen K., 2002). These features are consistent with the well-documented FTIR profile of commercial PAN fiber (Bilba N., Bilba D., and Moroi G., 2004).

Figure 1. FTIR spectrum of the initial PAN fiber before chemical modification, showing the characteristic nitrile absorption at 2241 cm^{-1}

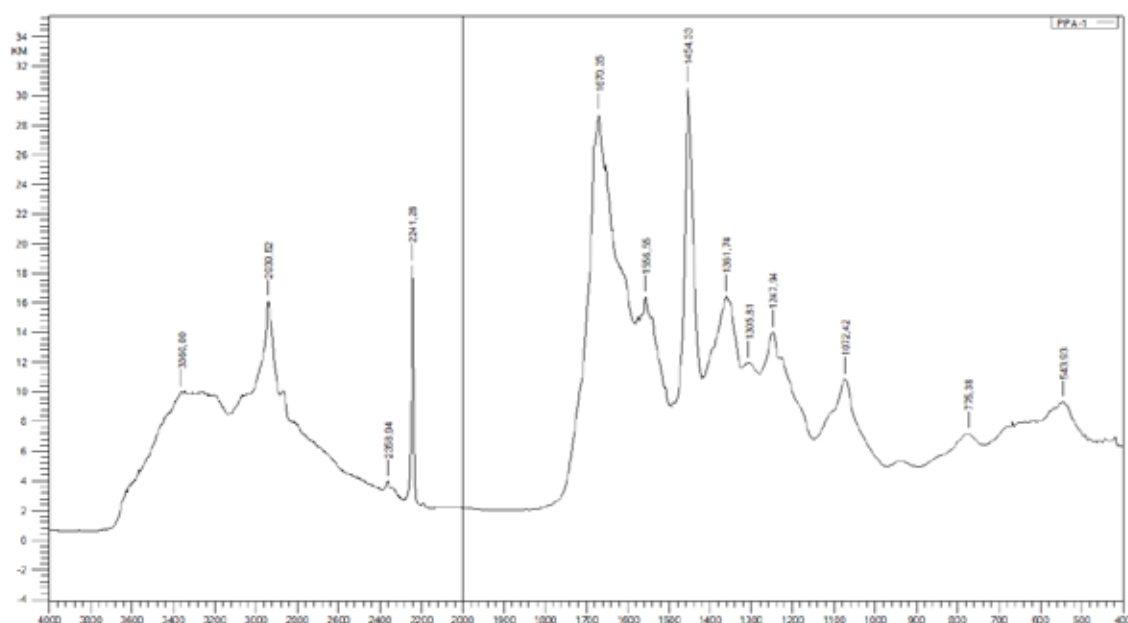


3.2 FTIR Analysis of Synthesized PPA Fiber

After conversion to PPA fiber through the sequential modification steps, the FTIR profile changed substantially (Figure 2). A broad band centered near 3360 cm^{-1} appeared, indicating the introduction of hydroxyl (O–H) and amine (N–H) functionalities. The nitrile band at 2241 cm^{-1} was still detectable but

reduced in relative prominence, suggesting partial conversion rather than complete consumption of the PAN nitrile groups. This partial conversion is beneficial because the remaining nitrile segments preserve fiber mechanical integrity while the newly introduced polar groups provide chemical functionality (Saeed K., Haider S., Oh T.-J., and Park S.-Y., 2008).

Figure 2. FTIR spectrum of synthesized PPA fiber after hydrolysis, amination, PEPA grafting, and acid activation, showing the appearance of new bands related to nitrogen- and oxygen-containing functional groups

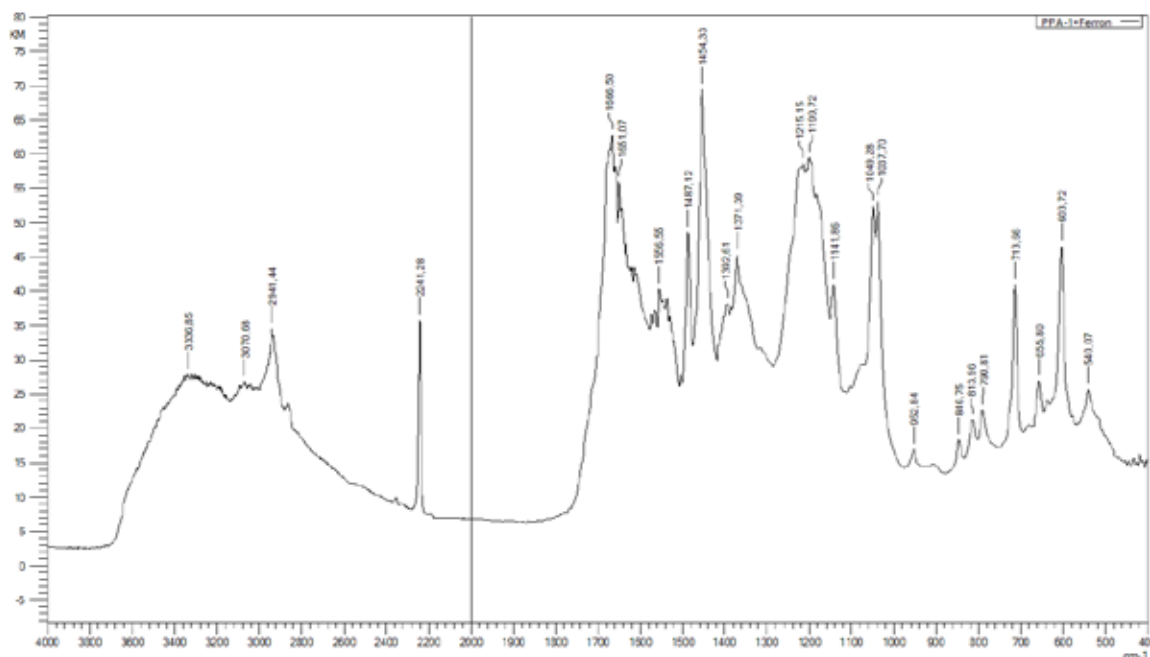


New and intensified bands were observed at 1670, 1557, 1454, 1362, 1306, 1248, 1072, 775, and 544 cm^{-1} . The bands at 1670 and 1557 cm^{-1} are assigned to C=O stretching (amide I) and N–H bending (amide II) of amide and amidoxime groups, respectively (Huang F., Xu Y., Liao S., Yang D., Hsieh Y.-L., and Wei Q., 2013; Zhao H., Liu X., Yu M. Wang Z., Zhang B., Ma H., Wang M., and Li J., 2015). The broad absorption in the 1300–1000 cm^{-1} region includes C–N stretching vibrations from amine and amidoxime functionalities. These spectral changes confirm the successful introduction of amide, amidoxime, imine/amine, and PEPA-associated functional groups on the fiber.

3.3 FTIR Analysis of Ferron-Immobilized PPA Fiber

Ferron immobilization produced further changes in the FTIR spectrum (Figure 3).

Figure 3. FTIR spectrum of PPA fiber after immobilization with Ferron (7-iodo-8-hydroxyquinoline-5-sulfonic acid), showing additional bands attributable to aromatic and sulfonate groups



3.4 Diffuse Reflectance Spectroscopy

Diffuse reflectance spectroscopy (DRS) confirmed a pronounced visible optical change after Ferron immobilization (Figure 4). The unmodified PPA fiber showed relatively low reflectance across the visible range, with a gradual decrease from shorter to longer wavelengths. In contrast, the

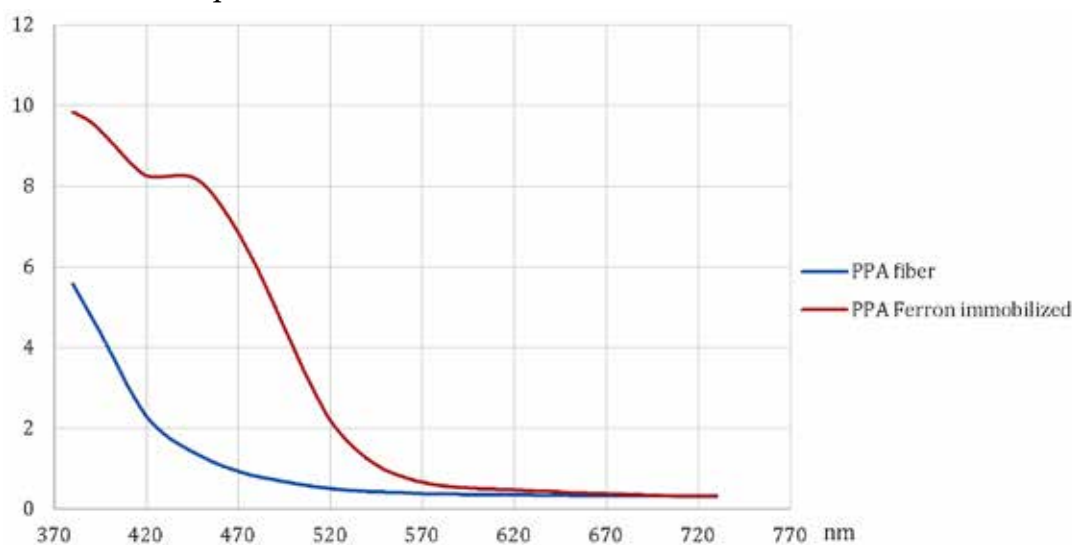
The broad high-wavenumber region was retained, with features near 3337, 3071, and 2941 cm^{-1} . Strong bands appeared at 1667, 1651, 1557, 1487, 1454, 1393, 1371, 1215, 1191, 1142, 1049, 1038, 953, 846, 814, 790, 714, 656, 604, and 540 cm^{-1} . The bands in the 1200–1000 cm^{-1} region are particularly informative: the sulfonic acid group ($-\text{SO}_3\text{H}$) of Ferron typically exhibits strong S=O stretching vibrations in this range (NIST Chemistry WebBook). Bands near 1487 and 1454 cm^{-1} are consistent with aromatic C=C stretching of the quinoline ring system. These spectral features indicate that Ferron was successfully retained on the PPA matrix, with its molecular structure intact after immobilization.

Ferron-immobilized PPA fiber displayed a significantly stronger reflectance response in the 380–520 nm region, followed by a pronounced decrease toward the baseline beyond approximately 520–570 nm. The two spectra converged at longer wavelengths, indicating that the major optical contribution of the immobilized Ferron occurs in the short-to-mid visible wavelength range.

The enhanced reflectance in the blue-green region is consistent with the known absorption properties of Ferron and its metal complexes (Cheng K. L., Ueno K., and Imamura T., 1992; Moldovan Z. and Neagu E. A., 2002). This optical response provides the basis for the intended use of the Ferron-PPA fiber as a solid-phase colorimetric sensor: when exposed to Fe(III), Fe(II), or Al(III) ions in aqueous solution, the

formation of metal–Ferron complexes on the fiber surface is expected to alter the reflectance spectrum in a concentration-dependent manner, enabling quantitative analysis. The differential optical response between the immobilized Ferron and its metal complexes can be captured by the EFI ES-2000 color calibrator spectrophotometer and correlated with metal-ion concentration.

Figure 4. Diffuse reflectance spectra of synthesized PPA fiber and Ferron-immobilized PPA fiber recorded with an EFI ES-2000 color calibrator spectrophotometer. The enhanced response at 380–520 nm is attributable to the immobilized Ferron



4. Discussion

The sequential modification strategy described in this study successfully converted PAN fiber into a chemically activated PPA fiber suitable for reagent immobilization. The alkaline hydrolysis step likely generated a more hydrophilic surface and introduced carboxylate and amide sites, making the fiber more accessible to subsequent nucleophilic modification. The amination step introduced nitrogen-containing functional groups, while PEPA grafting increased the density of amine sites that can participate in electrostatic, hydrogen-bonding, and coordination-related interactions with the Ferron molecule (Shahidova D. and Gafurova D., 2024).

The FTIR results are consistent with this interpretation. The retention of the nitrile band at 2241 cm⁻¹ in the PPA spectrum indicates that the reaction conditions produced a partially modified PAN backbone rather than complete degradation or exhaustive conversion. This is advantageous for fiber

stability, because unconverted PAN segments can preserve mechanical integrity while the newly introduced amine, amidoxime, and amide-related groups provide chemical functionality. The broad 3360 cm⁻¹ band and the intensified mid-infrared absorptions in the PPA spectrum are consistent with successful introduction of polar groups as reported in similar modification studies (Saeed K., Haidar S., Oh T.-J., and Park S.-Y., 2008; Huang F., Xu Y., Liao S., Yang D., Hsieh Y.-L., and Wei Q., 2013; Zhao H., Liu X., Yu M. Wang Z., Zhang B., Ma H., Wang M., and Li J., 2015).

Ferron immobilization is the critical step that enables the future application of this material for metal-ion sensing. Ferron forms colored complexes with Fe(III), Fe(II), and Al(III) through coordination involving the 8-hydroxyquinoline moiety (Cheng K. L., Ueno K., and Imamura T., 1992; Moldovan Z. and Neagu E. A., 2002). The FTIR spectrum after immobilization showed additional bands attributable to aromatic and sulfonated Ferron

groups, and the DRS spectrum demonstrated a strong optical response in the visible region compared with unmodified PPA. Together, these results confirm that Ferron was retained on the PPA matrix and that immobilization changed the reflectance behavior of the fiber in a measurable and reproducible way.

The choice of PEPA as the grafting agent merits specific discussion. PEPA is a branched polyamine containing primary, secondary, and tertiary amine groups, providing multiple types of binding sites for the immobilization of anionic or zwitterionic species such as Ferron (which carries a sulfonate group at $\text{pH} > 2-3$). Shahidova and Gafurova (Shahidova D. and Gafurova D., 2024) reported that PEPA modification of hydroxylamine-activated PAN fiber yielded a sorbent with a static exchange capacity of up to 5.4 mg-eq/g, indicating a high density of functional groups. The acid activation step (0.1 M HCl, 24 h) employed in the present work serves to protonate these amine groups, generating positively charged ammonium sites that can interact electrostatically with the negatively charged sulfonate group of Ferron, thereby enhancing reagent retention.

The DRS results are particularly notable because they demonstrate that Ferron retains its chromogenic properties after immobilization. In solution-phase applications, Ferron exhibits strong absorption in the near-UV to blue region of the spectrum (Cheng K. L., Ueno K., and Imamura T., 1992). The enhanced reflectance observed in the 380–520 nm range for the immobilized Ferron corresponds to the same electronic transitions. This indicates that the immobilization process does not disrupt the conjugated π -electron system responsible for the chromogenic behavior. The convergence of the PPA and Ferron-PPA spectra at longer wavelengths confirms that the observed difference is specifically due to the immobilized reagent rather than any modification-induced changes in the PPA substrate itself.

It should be noted that the present study focused on the synthesis and preliminary spectroscopic characterization of the Ferron-PPA material. For practical application to wastewater analysis, additional studies are required

to establish: (i) the optimal pH conditions for metal-ion binding and color development; (ii) calibration curves relating metal-ion concentration to the DRS response; (iii) detection limits and linear dynamic ranges for each target metal ion; (iv) selectivity and interference from coexisting ions; (v) repeatability and batch-to-batch reproducibility; and (vi) recovery from spiked real wastewater samples. These studies are the subject of ongoing work and will be reported in a subsequent publication.

5. Conclusion

A PEPA-modified polyacrylonitrile (PPA) fiber was successfully synthesized through a sequential four-step route involving alkaline hydrolysis, amination/amidoximation, PEPA grafting, and acid activation. Ferron (7-iodo-8-hydroxyquinoline-5-sulfonic acid) was subsequently immobilized onto the PPA fiber from aqueous solution.

FTIR spectroscopy confirmed the chemical transformations at each stage: (i) partial retention of the PAN nitrile groups with reduced intensity; (ii) appearance of a broad O–H/N–H band near 3360 cm^{-1} ; (iii) formation of amide (1670 cm^{-1}) and amidoxime/amine (1557 cm^{-1}) bands; and (iv) introduction of aromatic and sulfonate bands characteristic of Ferron after immobilization.

Diffuse reflectance spectroscopy revealed a distinct optical response from the Ferron-immobilized fiber in the 380–520 nm region, confirming that the immobilized reagent retains its chromogenic functionality. The macroscopic yellow coloration of the Ferron-PPA fiber provided qualitative visual confirmation of successful immobilization.

These results establish that PPA fiber is an effective solid support for Ferron immobilization and that the resulting material exhibits the spectroscopic properties necessary for the development of a solid-phase colorimetric sensor. Future work will focus on establishing the analytical performance characteristics of the Ferron-PPA fiber for the determination of Fe(III), Fe(II), and Al(III) ions in real and spiked wastewater samples.

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submitted 15.06.2026;

accepted for publication 29.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-17-23



PHYSICOMECHANICAL AND RHEOLOGICAL PROPERTIES OF COMPOSITE POLYMER GRANULES PREPARED FROM POLYPROPYLENE AND POLYETHYLENE WASTE REINFORCED WITH MINERAL FILLERS

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Cite: Tukhtaev F.S., Musoyeva D.N., Negmatov S.S. (2026). *Physicomechanical and Rheological Properties of Composite Polymer Granules Prepared From Polypropylene and Polyethylene Waste Reinforced With Mineral Fillers*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-17-23>

Abstract

This study prepared composite polymer granules based on polypropylene (PPJ160) and high-density polyethylene (HDPE 7000F) waste modified with bentonite and calcium carbonate (CaCO₃), and comprehensively investigated their physicomechanical and rheological properties. The compositions were compounded using a twin-screw extruder, and the melt flow index (MFI), tensile strength, elongation at break, flexural strength, elastic modulus, and impact toughness were determined using standard test methods. The results showed that increasing the HDPE content improved the flowability and deformability of the composites, while slightly reducing their tensile strength. Bentonite-modified composites demonstrated higher tensile strength and elongation, whereas the addition of CaCO₃ increased flexural strength and elastic modulus. The PHBC series exhibited superior structural properties. PHBC-1, containing 70% PPJ160, 10% HDPE, 5% MAPP, 10% bentonite, and 5% CaCO₃, was recommended as the optimal composition. The obtained results confirm the possibility of producing high-performance composite granules through the integrated recycling of polymer waste with local mineral fillers.

Keywords: polypropylene, polyethylene, composite, polymer, granules, bentonite, calcium carbonate, MAPP, rheology, material

Introduction

The recycling of polymer waste has become an important approach to mitigating environmental pollution and promoting the efficient utilization of secondary raw mate-

rials. In particular, the modification of polypropylene (PP) and high-density polyethylene (HDPE) waste with mineral fillers has attracted considerable attention due to its potential for producing composite materials

with enhanced performance characteristics. Bentonite is widely used as a reinforcing filler because of its high specific surface area and excellent reinforcing capability, whereas calcium carbonate (CaCO_3) improves the stiffness and flexural strength of polymer composites. In addition, maleic anhydride-grafted polypropylene (MAPP) acts as an effective compatibilizer, enhancing the interfacial adhesion between polymer phases and improving the overall mechanical performance of the composites. The present study aims to prepare composite polymer granules based on polypropylene and polyethylene waste modified with bentonite and CaCO_3 , to evaluate their rheological and physicomechanical properties, and to identify the optimum composition for potential applications in the production of construction materials.

Materials and Methods

Composite polymer granules prepared from polypropylene waste (PPJ160), high-density polyethylene (HDPE 7000F), maleic anhydride-grafted polypropylene (MAPP) as a compatibilizer, bentonite, and calcium carbonate (CaCO_3) were used as the materials for this study. To evaluate the reinforcing effect of bentonite and the stiffening effect of CaCO_3 , two groups of composite formulations were prepared. The first group (PHB) contained 10 wt.% bentonite, whereas the second group (PHBC) consisted of 10 wt.% bentonite and 5 wt.% CaCO_3 . The compositions of the prepared composite formulations are presented in (Table 1).

Table 1. Composition of Composite Polymer Granules Prepared from Polypropylene and Polyethylene Waste with Mineral Fillers

Sample Code	PPJ160 (wt.%)	HDPE 7000F (wt.%)	MAPP (%)	Bentonite (wt.%)	CaCO_3 (wt.%)
PHB-1	75	10	5	10	–
PHB-2	70	15	5	10	–
PHB-3	65	20	5	10	–
PHB-4	60	25	5	10	–
PHB-5	55	30	5	10	–
PHBC-1	70	10	5	10	5
PHBC-2	65	15	5	10	5
PHBC-3	60	20	5	10	5
PHBC-4	55	25	5	10	5
PHBC-5	50	30	5	10	5

Prior to the preparation of the composite granules, PPJ160 polypropylene waste and HDPE 7000F were shredded, while bentonite and calcium carbonate (CaCO_3) were dried at 105 °C to remove moisture. All components were weighed according to the specified formulations and dry-mixed in a laboratory mixer for 10–15 min. The prepared mixtures were compounded using a twin-screw extruder at processing temperatures ranging from 170 to 210 °C and a screw rotation speed of 60 ± 5 rpm. The extrudates were subsequently cooled in a water bath and pelletized into granules with a size of 3–5 mm. Before testing, all specimens were

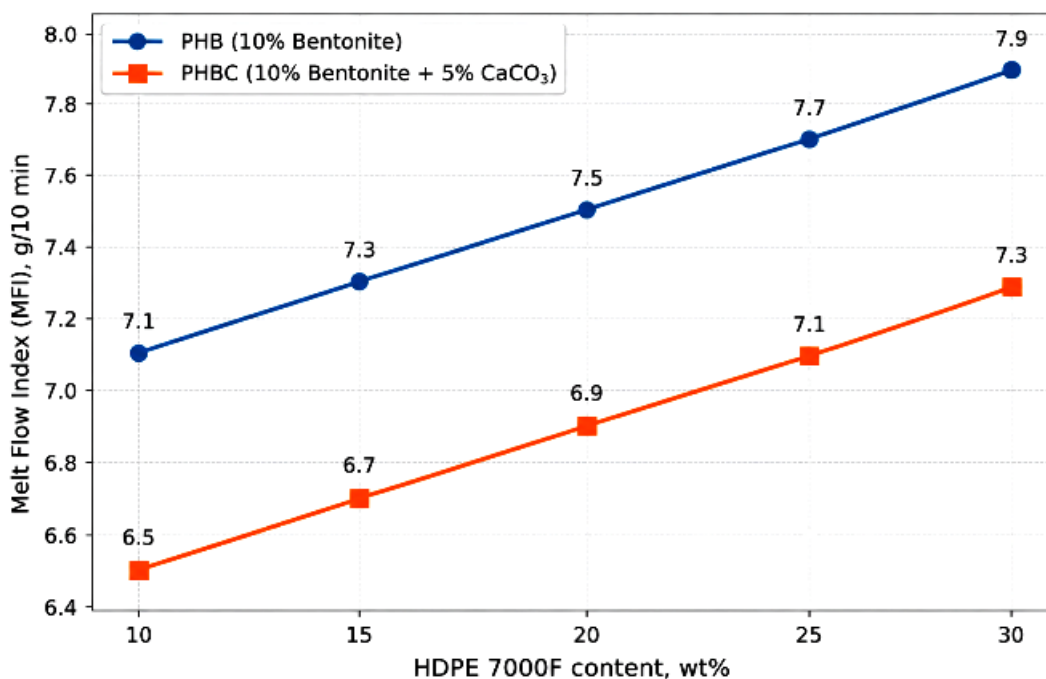
conditioned at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for at least 24 h. The processing characteristics of the composite granules were evaluated by measuring the melt flow index (MFI) according to ASTM D1238 (ISO 1133) at 230 °C under a load of 2.16 kg. The MFI values were expressed in g/10 min. The tensile properties, including tensile strength and elongation at break, were determined using a universal testing machine in accordance with ASTM D638 (ISO 527–2). The maximum tensile stress (MPa) and elongation at break (%) were recorded during testing. The flexural strength and flexural modulus were measured using the three-point

bending method following ASTM D790 (ISO 178). The maximum flexural stress (MPa) and flexural modulus (GPa) were calculated. The impact strength of the composite granules was evaluated using the Izod impact test in accordance with ASTM D256 (ISO 180). The impact resistance was expressed as absorbed impact energy in kJ/m². For each formulation, at least five specimens were tested. The experimental data were processed and reported as mean $\pm$ standard deviation (Mean $\pm$ SD). A comparative analysis was performed to evaluate the effects of HDPE 7000F, bentonite, and CaCO₃ contents on the rheological and physicomaterial properties of the composite materials.

Results and Discussion

The melt flow index (MFI) is one of the most important parameters for evaluating the processing characteristics of composite polymer granules. It characterizes the flow behavior of the polymer melt and provides an assessment of the material's suitability for processing techniques such as extrusion, injection molding, and other polymer-forming operations. Therefore, the MFI values of composite granules prepared from PPJ160, HDPE 7000F, MAPP, bentonite, and bentonite/CaCO₃ were investigated. The experimental results are presented in (Figure 1).

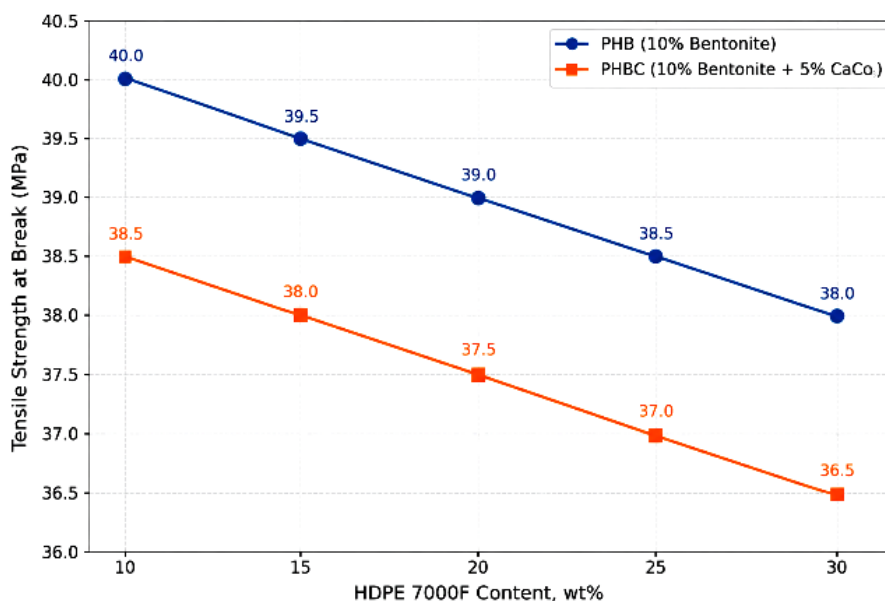
Figure 1. Effect of HDPE 7000F Content on the Melt Flow Index (MFI) of PHB and PHBC Composite Granules



A comparative analysis of the PHB and PHBC series (Figure 1) showed that the MFI values of the PHBC composites were consistently lower than those of the corresponding PHB formulations. For example, at an HDPE content of 20 wt.%, the MFI decreased from 7.5 g/10 min for PHB-3 to 6.9 g/10 min for PHBC-3, and a similar trend was observed for all formulations. This reduction is attributed to the addition of 5 wt.% CaCO₃, which, together with bentonite, forms a dispersed phase within the polymer matrix, restricts polymer chain mobility, and increases melt viscosity.

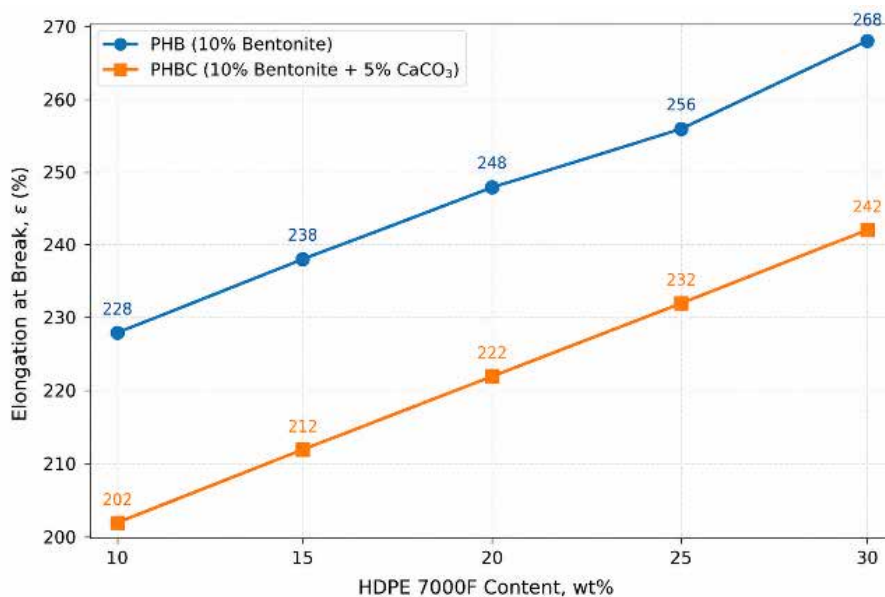
Nevertheless, the reduction in MFI was moderate, indicating that CaCO₃ had only a limited effect on the processability of the composites. The highest MFI values were recorded for PHB-5 (7.9 g/10 min) and PHBC-5 (7.3 g/10 min). Overall, the MFI values ranged from 6.5 to 7.9 g/10 min, demonstrating that all formulations possessed sufficient flowability for extrusion and pelletizing processes.

The tensile strength of the PHB and PHBC series of composite polymer granules was also investigated. The experimental results are presented in (Figure 2).

Figure 2. *Effect of HDPE 7000F Content on the Tensile Strength of PHB and PHBC Composite Granules*

As shown in Figure 2, the tensile strength decreased gradually with increasing HDPE 7000F content in both the PHB and PHBC series. In the PHB series, tensile strength (σ_t) decreased from 40.0 MPa (PHB-1) to 38.0 MPa (PHB-5), while in the PHBC series it declined from 38.5 MPa to 36.5 MPa. The highest tensile strength was obtained for PHB-1, owing to its higher PPJ160 content (75

wt.%). Increasing the HDPE content from 10 to 30 wt.% enhanced composite deformability but slightly reduced tensile strength because of the lower fraction of the reinforced crystalline polypropylene phase. The relatively small decrease (only 2 MPa in the PHB series) indicates that MAPP and bentonite effectively improved interfacial adhesion and reinforcement within the polymer matrix.

Figure 3. *Effect of HDPE 7000F Content on the Elongation at Break of PHB and PHBC Composite Granules*

The PHBC series consistently exhibited lower tensile strength than the corresponding PHB formulations. For instance, the

tensile strength decreased from 39.0 MPa for PHB-3 to 37.5 MPa for PHBC-3. This reduction is attributed to the incorporation of

5 wt.% CaCO_3 , which increases stiffness but also creates stress concentration sites during tensile loading, thereby limiting deformation and slightly reducing tensile strength. Overall, the results demonstrate that bentonite-modified composites provide more effective reinforcement than bentonite/ CaCO_3 -filled systems in the PPJ160/HDPE matrix.

In addition, the elongation at break of the PHB and PHBC series of composite polymer granules was investigated. The experimental results are presented in Figure 3.

As shown in Figure 3, the elongation at break increased steadily with increasing HDPE 7000F content in both the PHB and PHBC series. In the PHB series, elongation at break (ϵ) increased from 228% (PHB-1) to 268% (PHB-5), while in the PHBC series it increased from 202% to 242%. This improvement is attributed to the higher ductility of HDPE compared with polypropylene, which enhances composite flexibility and promotes greater polymer chain orientation during tensile deformation. The highest elongation at break was obtained for PHB-5 (268%), while MAPP further improved interfacial adhesion between the PPJ160 and HDPE phases, preserving composite integrity during deformation. Although the PHBC series exhibited the same increasing trend, its elongation at break remained consistently lower than that of the corresponding PHB formulations. For example, PHB-3 showed an elongation at break of

248%, compared with 222% for PHBC-3. On average, the PHBC composites exhibited 20–30% lower elongation than the PHB series. This reduction is attributed to the incorporation of 5 wt.% CaCO_3 , whose particles restrict polymer chain mobility and reduce the plastic deformation capability of the matrix. These results indicate that bentonite-modified composites exhibit superior deformation properties while maintaining greater flexibility than bentonite/ CaCO_3 -filled systems. Overall, the highest impact strength among the investigated composites was observed for the PHB-5 formulation, reaching 39 kJ/m², whereas the lowest value was recorded for PHBC-1 (33 kJ/m²). The impact strength (a_n) of all composite formulations ranged from 33 to 39 kJ/m², indicating that the prepared materials possess sufficient resistance to dynamic loading and impact stresses. The physicomechanical and rheological properties of composite polymer granules prepared from PPJ160, HDPE 7000F, MAPP, bentonite, and CaCO_3 were comprehensively evaluated. The PHBC series exhibited superior physicomechanical performance compared with the PHB series. In particular, PHBC-1 demonstrated the highest flexural strength (64 MPa) and flexural modulus (2.29 GPa), indicating excellent stiffness and structural performance for construction applications. These findings are further supported by the physicomechanical and rheological data summarized in Table 2.

Table 2. *Physicomechanical and Rheological Properties of Composite Polymer Granules Modified with Inorganic Mineral Fillers*

Sample ID	(MFI) g/10 min	Tensile Strength σ_t , MPa	Elongation at Break ϵ , %	Flexural Strength σ_f , MPa	Flexural Modulus E_{exp} , GPa	Impact Strength a_n , kJ/m ²
PHB-1	7,1	40,0	228	62	2,14	35
PHB-2	7,3	39,5	238	61	2,09	36
PHB-3	7,5	39,0	248	60	2,04	37
PHB-4	7,7	38,5	258	59	1,99	38
PHB-5	7,9	38,0	268	58	1,94	39
PHBC-1	6,5	38,5	202	64	2,29	33
PHBC-2	6,7	38,0	212	63	2,24	34
PHBC-3	6,9	37,5	222	62	2,19	35
PHBC-4	7,1	37,0	232	61	2,14	36
PHBC-5	7,3	36,5	242	60	2,09	37

Among the investigated formulations, PHBC-1 (70 wt.% PPJ160, 10 wt.% HDPE 7000F, 5 wt.% MAPP, 10 wt.% bentonite, and 5 wt.% CaCO_3) was identified as the optimum composition because of its balanced combination of stiffness, flexural strength, elastic modulus, and impact resistance. This formulation is considered a promising material for manufacturing construction profiles, façade panels, decorative cladding, cable ducts, and other structural products. The incorporation of 15 wt.% mineral fillers (10 wt.% bentonite and 5 wt.% CaCO_3) resulted in the best mechanical performance, demonstrating the effectiveness of locally available mineral fillers in reinforcing polymer waste-based composites. These findings confirm that the integrated recycling of polymer waste and mineral fillers is a feasible approach for producing high-performance composite granules for engineering and construction applications.

Conclusion

Composite polymer granules based on polypropylene (PPJ160) and high-density polyethylene (HDPE 7000F) waste, modi-

fied with bentonite and calcium carbonate (CaCO_3), were successfully prepared, and their rheological and physicomaterial properties were comprehensively evaluated. The results demonstrated that increasing the HDPE content enhanced the melt flow index and elongation at break, while causing a slight reduction in tensile strength. The bentonite-modified PHB series exhibited superior tensile strength and deformation properties, whereas the PHBC series containing CaCO_3 showed improved flexural strength and flexural modulus. Among the investigated formulations, PHBC-1 (70 wt.% PPJ160, 10 wt.% HDPE, 5 wt.% MAPP, 10 wt.% bentonite, and 5 wt.% CaCO_3) was identified as the optimum composition because it provided the best balance of mechanical and processing properties. These findings demonstrate that the integrated recycling of polymer waste with locally available mineral fillers offers an effective approach for producing high-performance composite polymer granules suitable for construction materials and other structural engineering applications.

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submitted 14.06.2026;

accepted for publication 28.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-24-30



A HYBRID SORPTION-SPECTROSCOPIC APPROACH FOR TITANIUM(IV) DETERMINATION BASED ON CONGO RED IMMOBILIZED ONTO SILK FIBROIN

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Cite: Gofurov A.A., Smanova Z.A., Shahidova D.N., Usmanova H.U. (2026). A Hybrid Sorption-Spectroscopic Approach for Titanium(IV) Determination Based on Congo Red Immobilized onto Silk Fibroin. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-24-30>

Abstract

A new hybrid sorption-spectroscopic method for the determination of trace amounts of titanium(IV) ions has been developed. The method is based on the immobilization of an organic reagent, Congo Red (CR), onto a natural polymer matrix – silk fibroin (SF). The complexation conditions of Ti(IV) with various organic azo- and hydroxyl-containing reagents were screened in different buffer systems within a pH range of 2.6 to 7.1. It was established that Congo Red selectively forms a stable dark-blue complex with Ti(IV) in an acetate buffer solution at an optimum pH of 4.6, shifting the absorption maximum from 500 nm (reagent) to 575 nm (complex). Among the evaluated sorbents (PPA, PPD, PPM, and silk fibroin), silk fibroin demonstrated superior sorption capacity toward Congo Red. The immobilized matrix changes color upon contact with Ti(IV) ions, showing a diffuse reflectance maximum at $\lambda = 585$ nm. The linear range of the analytical signal obeying the Beer-Lambert law is 8–48 $\mu\text{g/L}$ of Ti(IV). The accuracy of the method was validated using artificial solutions, yielding a relative standard deviation (Sr) of less than 0.022. The structural and elemental fixation of the reagent and subsequent sorption of titanium onto the matrix were confirmed by X-ray fluorescence (XRF) analysis, indicating a titanium mass fraction of 2.49% in the target complex.

Keywords: Titanium(IV), Congo Red, Silk fibroin, Sorption-spectroscopic method, Immobilization, Solid-phase spectrophotometry, X-ray fluorescence analysis

Introduction

Titanium and its compounds play a pivotal role in modern industrial sectors, ranging from metallurgy and chemical manufactur-

ing to the production of pigments, cosmetics, and advanced biomaterials. However, the inevitable expansion of industrial activities contributes to the progressive accumulation

of titanium(IV) ions in environmental matrices and natural aquatic systems. Although titanium species are generally classified as possessing low systemic toxicity compared to heavy metals, persistent exposure to elevated concentrations can trigger cellular oxidative stress and potentially disturb fragile ecological balances (Zhu, 2026). Consequently, developing highly sensitive, rapid, and cost-effective analytical techniques for the determination of trace titanium(IV) amounts remains a crucial task for environmental monitoring and industrial quality control (Madakkaruppan, 2026).

To date, sophisticated instrumental methods such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) have served as the standard benchmarks for trace metal analysis (Falila, 2026). Despite providing exceptional sensitivity and low detection limits, these advanced techniques are frequently constrained by high equipment costs, the need for specialized laboratory infrastructure, and complex, time-consuming sample preparation protocols that prevent on-site, real-time measurements (Gomes, 2025). Traditional solution-based spectrophotometry offers a significantly more economical alternative, yet it often fails to deliver adequate sensitivity when isolating sub-microgram quantities of target analytes and remains highly susceptible to spectral interferences caused by co-existing transition metal ions (Miura, 2025).

To address these challenges, hybrid analytical strategies that integrate solid-phase extraction with direct optical detection have gained widespread traction. By immobilizing a selective organic chromogenic reagent onto a solid support, target ions can be preconcentrated from large liquid volumes and directly quantified on the substrate using solid-phase spectrophotometry or diffuse reflectance spectroscopy (Madusmanova, 2020). This integrated methodology drastically amplifies both the analytical signal intensity and the selectivity of the system, effectively neutralizing the background matrix effects of complex environmental samples without requiring tedious extraction steps (Krasnodębska, 2025).

The critical cornerstone in optimizing these hybrid analytical frameworks lies in the

deliberate choice of the solid matrix. While synthetic polymeric sorbents have historically dominated this domain due to their uniform structural architectures, the paradigms of green chemistry have shifted focus toward natural biopolymers. Compelling data reveals that natural sorbents are fully comparable, and in many operational scenarios clearly superior, to their synthetic counterparts (Raut, 2024). Possessing high structural biodegradability, low processing costs, and an exceptional density of native functional groups – such as amino, hydroxyl, and carboxyl units – natural matrices facilitate the stable, spontaneous immobilization of organic ligands through non-covalent and electrostatic interactions without relying on toxic cross-linking chemical agents (Kuminova, 2023).

Among these sustainable candidates, silk fibroin emerges as an exceptionally viable protein matrix for advanced optical test systems due to its robust mechanical strength, high transparency, and chemical resilience (He, 2023). Its porous structure ensures accelerated mass transfer and rapid target ion diffusion during sorption. This research aims to establish a highly selective and sensitive hybrid sorption-spectroscopic method for tracking trace titanium(IV) levels using Congo Red immobilized onto natural silk fibroin (de Higuera, 2022). We outline the optimization of complexation kinetics, compare the system against common synthetic sorbents, and validate it using diffuse reflectance spectroscopy and X-ray fluorescence analysis (Jayawardene, 2021).

Research method

In our study, the research process was divided into several key stages:

1. Investigation of organic reagents and medium optimization. The possibility of complex formation between titanium(IV) ions and six organic reagents (magneson-I, Congo Red, Arsenazo III, tropaeolin O, aluminon, and naringin) was evaluated across a wide pH range (2.6–7.1) using glycine, acetate, and ammonium acetate buffer solutions. At the conclusion of this stage, the most suitable reagent was selected.

2. Spectrophotometric studies in solution. The absorption spectra of the initial reagents and their corresponding

complexes with Ti(IV) were recorded; the maximum light absorption wavelengths (λ_{max}) and the optimum pH values were determined.

3. Selection of the polymer matrix.

The sorption capacity of various carriers – specifically the synthetic sorbents PPA, PPD, and PPM, as well as the natural biopolymer silk fibroin – was investigated with respect to the selected organic reagent.

4. Sorption and structural studies of the modified sorbent. The spectral characteristics of the immobilized test system were evaluated, the diffuse reflectance spectra of the complex on the matrix were investigated, and the linearity limits obeying the fundamental law of light absorption (the Bouguer–Lambert–Beer law) were established.

5. Method validation and characterization. The analysis of model (artificial) solutions was performed along with the evaluation of metrological parameters (S, Sr). Additionally, direct confirmation of elemental fixation was achieved using X-ray fluorescence (XRF) analysis.

Results

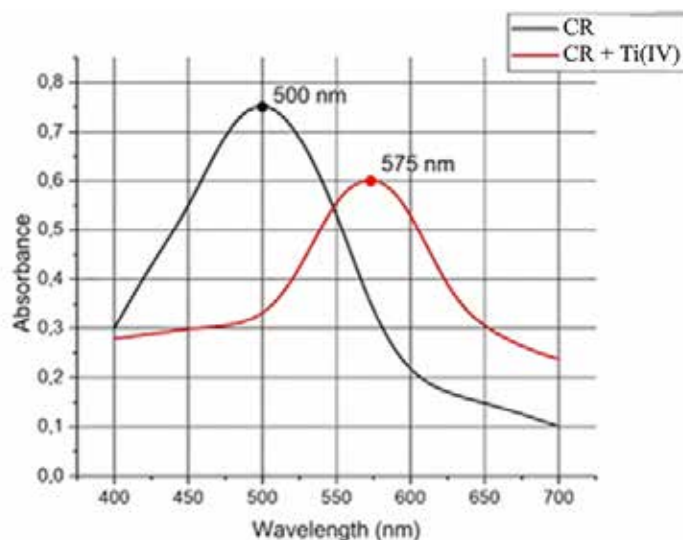
Given that the analytical signal in this study was planned to be acquired spectrophotometrically – by measuring absorbance for solution-based analysis and reflectance for solid-phase (sorbent) analysis – we investigated the feasibility of complex formation between various reagents and titanium(IV) ions across different media and pH levels (Table 1).

Table 1. Evaluated organic reagents, buffer systems, and pH values examined for complex formation with titanium(IV) ions

	Glycine buffer				Acetate buffer				Ammonium acetate buffer	
pH	2.6	3.0	3.6	4.2	4.6	5.2	5.6	6.2	6.7	7.1
Magneson I	–	–	–	–	–	–	–	–	–	–
Congo Red	–	–	–	+	+	+	–	–	–	–
Ars III	–	–	–	–	–	–	–	–	–	–
Tropeolin O	–	–	–	–	–	–	–	–	–	–
Aluminon	–	–	–	–	–	–	–	–	–	–
Naringin	–	–	–	–	–	–	–	–	–	–

Note: “–” – complex not detected / analytical signal absent; “+” – complex formation detected

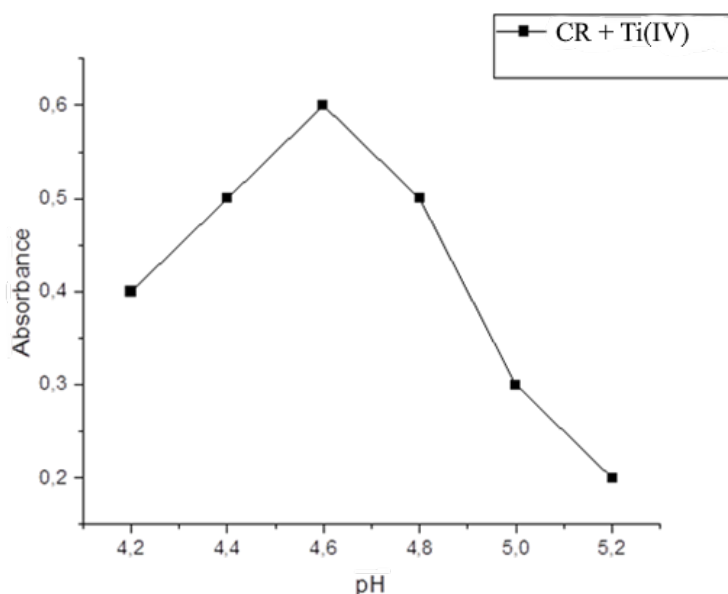
Figure 1. Light absorption spectra of the Congo Red reagent and its complex with titanium(IV) ions at pH = 4.6 (acetate buffer)



In our work, we tested several organic reagents, such as magneson-I, Congo Red, Arsenazo III, and tropaeolin O, which contain a diazo group that serves as an effective analytical group capable of complexation. Additionally, aluminon and naringin were evaluated, as they contain phenolic –OH groups bound to a benzene ring and also possess strong potential for forming coordination complexes with metal ions.

We succeeded in obtaining a complex through the interaction of the Congo Red reagent with titanium (IV) ions within a pH range of 4.2–5.1 in an acetate buffer medium. This complex exhibited an absorption maximum at $\lambda = 575$ nm. Its color also distinctly differed from that of the reagent itself (Congo Red, $\lambda = 500$ nm); the complex turned dark blue, in contrast to the bright red color of the initial reagent (Fig. 1).

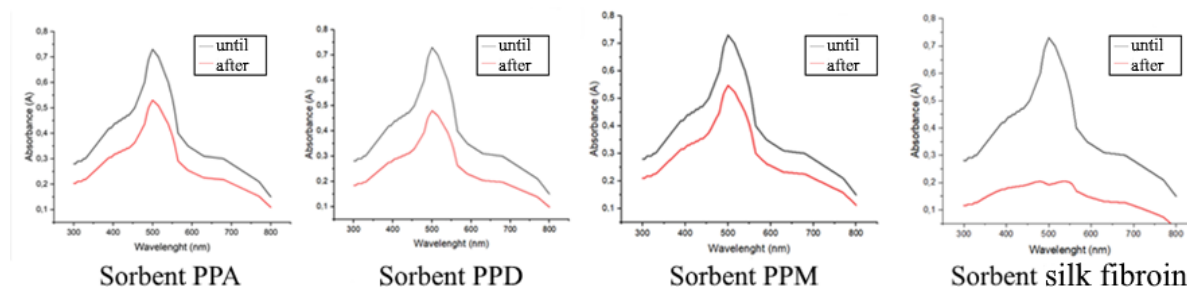
Figure 2. Light absorption of the complex at $\lambda = 575$ nm as a function of the medium pH (acetate buffer)



It was established that the maximum light absorption of the complex occurs at $\text{pH} = 4.6$. Consequently, all subsequent analyses were performed at this specific pH value to ensure the maximum analytical signal (Fig. 2).

Next, we proceeded with selecting a sorbent for our Congo Red reagent. We investigated its sorption onto various matrices, such as PPA, PPD, PPM, and silk fibroin. Silk fibroin proved to be the most effective sorbent for our reagent (Fig. 3).

Figure 3. Light absorption spectra of the Congo Red reagent solution before and after immersion of the sorbent for 30 minutes. ($C_{\text{CR}} = 20 \mu\text{g/L}$, $m_{\text{sorb.}} = 0.2 \text{ g}$, $V_R = 10 \text{ mL}$)



Upon immersion into a solution containing titanium(IV) ions, the reagent sorbed onto the fiber formed a complex, and the maximum reflectance of the result-

ing complex was observed at $\lambda = 585$ nm (Fig. 4).

Subsequently, the linear range within which the reflectance of the complex –

formed by the interaction of the Congo Red reagent immobilized onto silk fibroin fiber – obeyed the Bouguer–Lambert–Beer law was

determined. This linear range was found to be within the titanium(IV) ion concentration spectrum of 8 to 48 $\mu\text{g/L}$ (Fig. 5).

Figure 4. Dependence of the reflectance coefficient (Kubelka–Munk function) on the wavelength

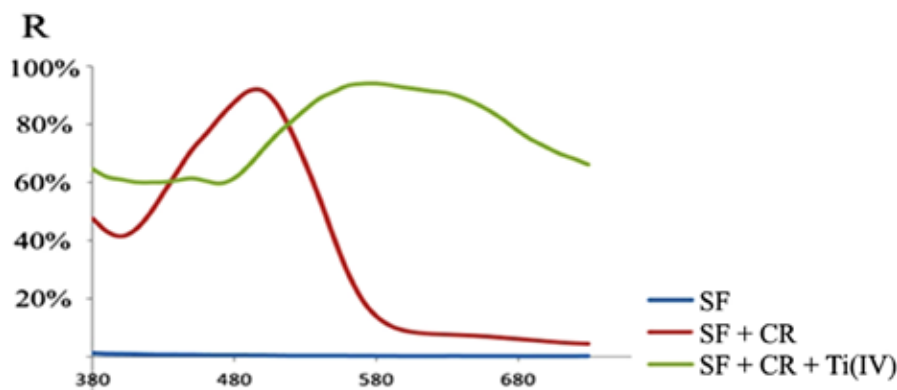
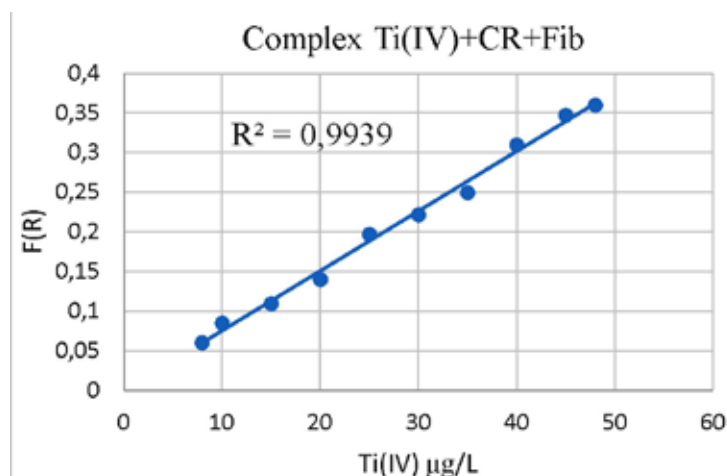


Figure 5. Linear range of the complex obeying the Bouguer-Lambert-Beer law



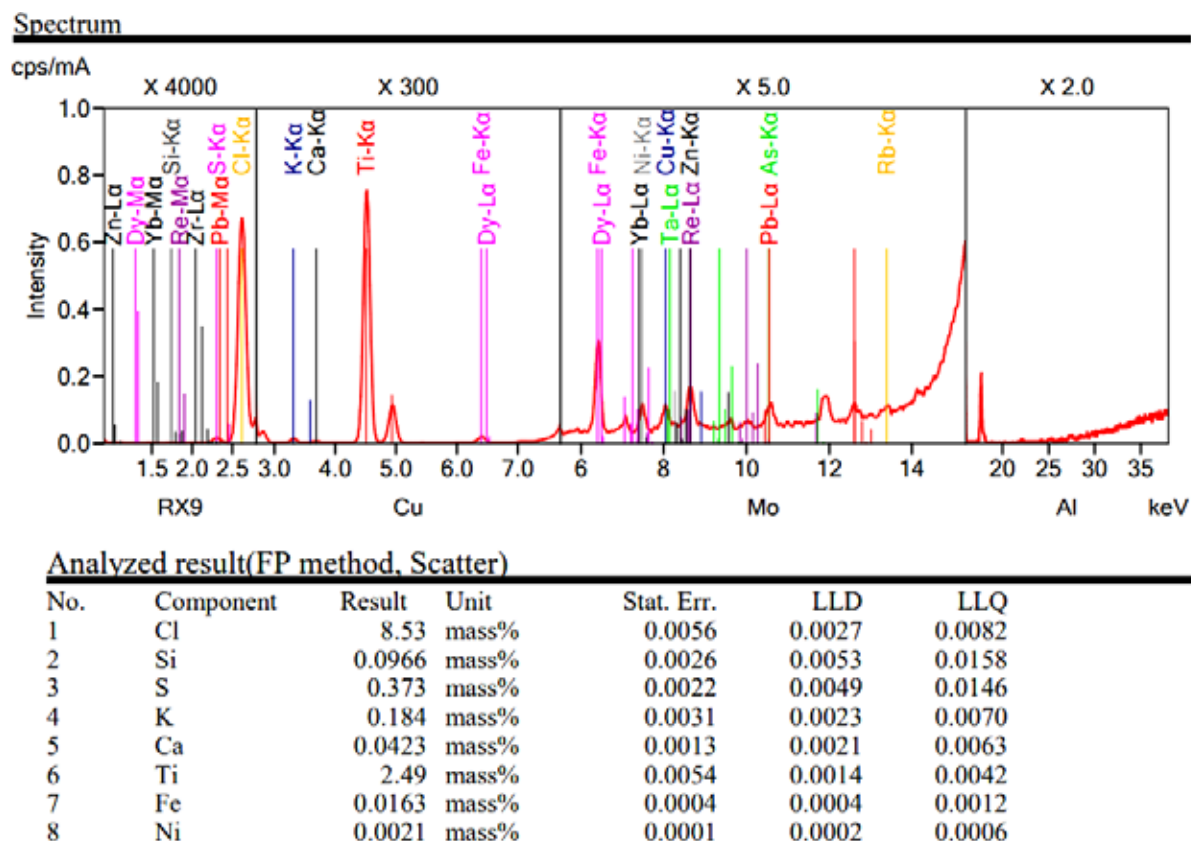
The developed procedure was tested on artificial solutions, which demonstrated its accuracy and feasibility (Table 2).

Table 2. Analysis of artificial solutions

Analyzed ion	System	Metal added, $\mu\text{g/L}$	Metal found, $\mu\text{g/L}$	S	S_r
Ti(IV)	Fib.: CR	9,0	9,09 $\pm$ 0,50	0,200	0,022
		19,0	19,10 $\pm$ 0,95	0,382	0,020
		29,0	29,11 $\pm$ 1,37	0,553	0,019

X-ray fluorescence (XRF) analysis confirmed the fixation of the reagent onto the silk fibroin fiber, as well as the sorption of titanium(IV) ions onto the modified fiber. The analysis showed that after the interaction of the modified fiber with the solu-

tion containing titanium(IV) ions, the mass fraction of the element titanium in the modified fiber was 2.49%, while the mass fraction of the element sulfur, which is part of the reagent, in the fiber was 0.373% (Fig. 6).

Figure 6. X-ray fluorescence analysis of the complex formed by the interaction of Congo Red immobilized onto silk fibroin with titanium(IV) ions

Conclusion

In the course of the conducted study, a new, highly sensitive, hybrid sorption-spectroscopic method for the determination of micro-amounts of titanium(IV) ions was developed and scientifically substantiated. Based on a comparative analysis of matrices and reagents, the optimal analytical system was selected: the organic reagent Congo Red immobilized on a natural protein carrier – silk fibroin.

The optimum conditions for extraction and the maximum development of a stable optical signal are an acetate buffer solution

medium at pH = 4.6 and a working wavelength of 585 nm in the solid phase. The method is characterized by a wide linear determination range (8–48 µg/L), rapid analysis time, high selectivity, and excellent metrological characteristics ($Sr \leq 0.022$). The reliability of dye fixation and the occurrence of target component sorption were confirmed by an independent physicochemical method of X-ray fluorescence analysis. The developed hybrid approach can be recommended for the creation of test systems for environmental monitoring and rapid analysis of environmental objects.

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submitted 20.05.2026;

accepted for publication 04.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-31-40



MODERN METHODS FOR THE SYNTHESIS OF 2-AMINO-6-OXYPURINE

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Cite: Oripov O. (2026). *Modern Methods for the Synthesis of 2-Amino-6-oxypurine*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-31-40>

Abstract

2-Amino-6-oxypurine (guanine) is an important purine base and a fundamental component of DNA and RNA. Due to its biological significance and pharmaceutical applications, the development of efficient synthetic methods for guanine remains an important research area. Classical approaches, such as the Traube synthesis, are effective but often require multistep procedures and high reaction temperatures.

Modern synthetic methods include the cyclization of 2,4,5-triamino-6-hydroxypyrimidine with formamide, where formamide acts as both solvent and formylating agent. The use of ZnCl_2 as a Lewis acid catalyst allows the reaction to proceed at lower temperatures with improved yields. In addition, microwave-assisted synthesis, one-pot reactions, and green chemistry approaches have been developed to enhance efficiency and reduce energy consumption.

The results demonstrate that catalytic formamide-mediated cyclization is a simple, efficient, and practical method for the synthesis of guanine and its biologically active derivatives.

Keywords: *guanine, 2-amino-6-oxypurine, purine derivatives, Traube synthesis, formamide cyclization, ZnCl_2 catalyst*

Introduction

At present, purine-based heterocyclic compounds are among the most important subjects of research in organic chemistry, pharmaceutical science, biotechnology, and molecular biology. Among these compounds, 2-amino-6-oxypurine, commonly known as guanine, occupies a special place. Guanine is one of the major nitrogenous bases found in DNA and RNA and plays a crucial role in the storage, transmission, and expression of genetic information. In addition, guanine and

its derivatives are widely used in the synthesis of biologically active compounds, pharmaceutical products, antiviral agents, and antitumor drugs. Therefore, the development and improvement of synthetic methods for guanine and its derivatives remain important directions in modern organic chemistry.

Purine derivatives participate in many essential biological processes, including energy metabolism, cell division, and nucleic acid biosynthesis. Adenine and guanine serve as fundamental components of nucleic

acids and are directly involved in genetic coding. The presence of an amino group, a carbonyl group, and several nitrogen atoms in the guanine molecule determines its high chemical reactivity. These structural features make guanine a convenient substrate for various chemical modifications, enabling the synthesis of novel biologically active substances, coordination compounds, and pharmaceutical agents (March's Advanced Organic Chemistry. 2020; Pavia D., Lampman G., Kriz G. S., Vyvyan J. R., 2021; Clayden J., Greeves N., Warren S., 2023; Mass Spectrometry. de Hoffmann E., Stroobant V. 2022).

Among the classical methods for guanine preparation, the Traube synthesis occupies a prominent position. Developed at the beginning of the twentieth century, this method is based on the construction of the purine ring system from aminopyrimidine derivatives. The Traube synthesis involves several sequential steps, including nitrosation, reduction, formylation, and cyclization. Although this method allows the targeted formation of the purine nucleus, its multistep nature and relatively high energy requirements are considered significant disadvantages.

In recent years, considerable attention has been devoted to the development of efficient and energy-saving methods for guanine synthesis. In particular, the cyclization of 2,4,5-triamino-6-hydroxypyrimidine in the presence of formamide has attracted increasing interest. In this approach, formamide acts simultaneously as a solvent and a formylating reagent. As a result, the number of reaction steps is reduced, the synthesis becomes technologically simpler, and product yields are improved. However, the reaction is commonly carried out at relatively high temperatures (170–180 °C), leading to increased energy consumption and the possibility of side reactions (Molecular Spectroscopy., Banwell C. N., McCash E. M. 2021; Zhang Y., Wang X., Li J., 2023).

To overcome these limitations, the application of catalytic systems has emerged as a promising strategy. In particular, zinc chloride, a Lewis acid catalyst, can activate the carbonyl group of formamide, thereby accelerating the formation of intermediate formamido compounds and facilitating intra-

molecular cyclization at lower temperatures. Consequently, the reaction temperature can be reduced while simultaneously improving product yield and decreasing energy consumption.

Today, guanine and its derivatives are extensively utilized in the pharmaceutical industry. They serve as key intermediates in the production of antiviral drugs, antimetabolites, immunomodulators, and other biologically active compounds. Furthermore, guanine derivatives are important building blocks in molecular biology, biotechnology, and agricultural chemistry for the development of new functional materials and biologically active agents. Therefore, the development of efficient methods for obtaining guanine in high yield is of considerable scientific and practical importance.

The aim of this work is to analyze modern methods for the synthesis of 2-amino-6-oxypurine, to investigate the cyclization of 2,4,5-triamino-6-hydroxypyrimidine in formamide in the presence of a ZnCl_2 catalyst, and to determine optimal reaction conditions for high-yield synthesis at reduced temperatures. The obtained results may contribute to the improvement of guanine production technologies and provide a basis for the synthesis of biologically active purine derivatives.

Materials and Methods

2-Amino-6-oxypurine (guanine) and its precursor compounds were selected as the objects of this study. The synthesis was carried out using 2,4,5-triamino-6-hydroxypyrimidine, formamide, formic acid, sodium hydroxide, ethanol, distilled water, and other analytical-grade reagents. All chemicals were used without further purification.

The synthesis of 2-amino-6-oxypurine was performed through the cyclization of 2,4,5-triamino-6-hydroxypyrimidine in formamide medium. In a typical procedure, 1.42 g (0.01 mol) of 2,4,5-triamino-6-hydroxypyrimidine was suspended in 20 mL of formamide, and 0.07 g (5 mol%) of ZnCl_2 was added as a Lewis acid catalyst. The reaction mixture was heated at 135–145 °C for 4 h under continuous stirring. After completion of the reaction, the mixture was cooled

to room temperature and poured into ice-cold water. The resulting precipitate was filtered, washed thoroughly with distilled water, and dried at 80–90 °C to afford guanine as a white crystalline solid.

As an alternative route, the alkaline hydrolysis of 2-amino-6-chloropurine was also investigated. In this method, 2-amino-6-chloropurine was refluxed in an aqueous sodium hydroxide solution. After completion of the reaction, the mixture was neutralized, and the resulting crystals of 2-amino-6-oxypurine were isolated by filtration, washed with water, and dried.

The physicochemical properties of the synthesized compounds were investigated using modern instrumental techniques. Melting points were determined by the capillary method. The progress of the reactions and the purity of the products were monitored by thin-layer chromatography (TLC) using silica gel plates and appropriate eluent systems.

The structures of the synthesized compounds were confirmed by Fourier-transform infrared spectroscopy (FT-IR), ultraviolet-visible spectroscopy (UV-Vis), proton and carbon nuclear magnetic resonance spectroscopy (^1H and ^{13}C NMR), and mass spectrometry. FT-IR spectra were recorded in the range of 4000–400 cm^{-1} and analyzed for characteristic absorption bands corresponding to amino and carbonyl groups. UV-Vis spectra were measured in solution to investigate electronic transitions within the purine system.

All experiments were performed at least three times. The obtained results were statistically processed, and the average values together with standard deviations were calculated. The efficiency of the synthetic procedures was evaluated based on product yield, purity, and physicochemical characteristics.

Results and Discussion

The Traube synthesis is one of the most important classical methods for the preparation of purine derivatives. Developed by the German chemist Wilhelm Traube in the early twentieth century, this approach is still widely employed for the synthesis of guanine, adenine, hypoxanthine, and their derivatives. The fundamental principle of the Traube reaction is the construction of the purine nu-

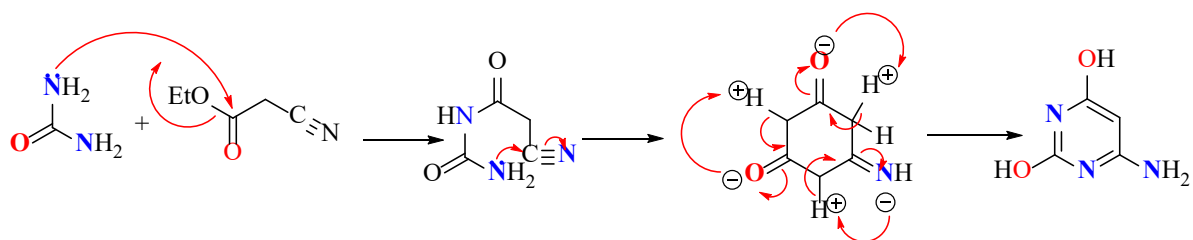
cleus through the formation of an imidazole ring from aminopyrimidine intermediates.

In the present study, the synthesis of 2-amino-6-oxypurine (guanine) was initiated through the condensation of urea with ethyl cyanoacetate. This reaction represents a key step in the formation of the pyrimidine precursor required for subsequent purine ring construction. The reaction proceeds through a multistep mechanism involving nucleophilic addition, elimination, cyclization, and tautomerization processes.

Initially, the amino group of urea attacks the electrophilic carbonyl carbon atom of ethyl cyanoacetate, leading to the formation of a tetrahedral intermediate. Subsequently, rearrangement of this intermediate occurs with the elimination of an ethoxy group, resulting in the formation of ethanol and an amide-type intermediate. In the next stage, the second amino group undergoes intramolecular nucleophilic attack on the electrophilic carbon atom of the nitrile group. This process initiates the formation of a new heterocyclic ring and leads to the construction of the pyrimidine framework.

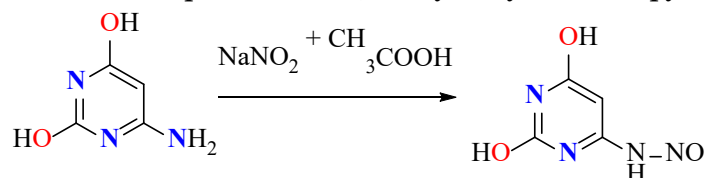
During the course of the reaction, several proton-transfer processes occur together with keto–enol and amino–imino tautomeric transformations. These rearrangements contribute to the formation of a thermodynamically stable aromatic pyrimidine system. As a result, 2,4-dihydroxy-5-aminopyrimidine is obtained as the major product and serves as a key intermediate in the synthesis of guanine.

The obtained pyrimidine derivative was subsequently converted into guanine through the classical Traube sequence involving nitrosation, reduction, formylation, and cyclization reactions. The resulting guanine was isolated in high purity and characterized by FT-IR, UV-Vis, and mass spectroscopic techniques. The spectral data confirmed the successful formation of the purine nucleus and were consistent with the expected structure of 2-amino-6-oxypurine. These results demonstrate that the proposed synthetic pathway is an efficient approach for the preparation of guanine and may serve as a basis for the synthesis of biologically active purine derivatives.



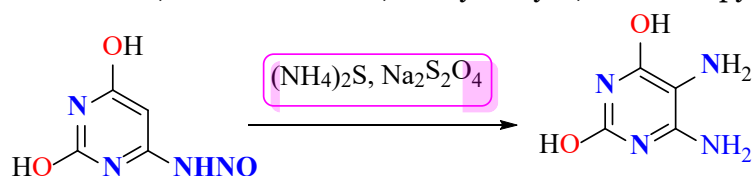
2,4-Dihydroxy-5-aminopyrimidine is nitrated with sodium nitrite in the presence

of acetic acid or a mineral acid. As a result, 2,4-dihydroxy-5-nitrosopyrimidine is formed.



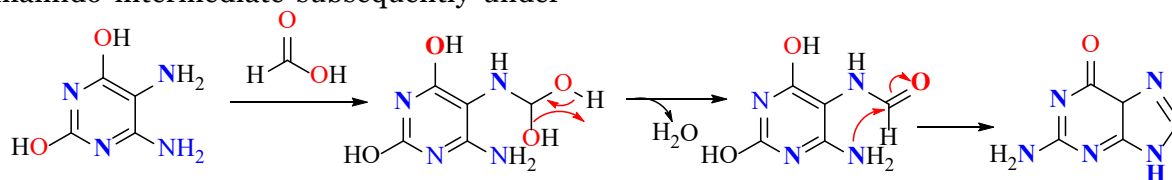
The resulting nitroso derivative is reduced using ammonium sulfide, sodium di-

thionite, or catalytic hydrogenation to afford 2,4-dihydroxy-5,6-diaminopyrimidine.



When diaminopyrimidine is heated with formic acid or formamide, the amino group undergoes formylation. The resulting formamido intermediate subsequently under-

goes intramolecular cyclization to form an imidazole ring, leading to the construction of the purine nucleus.



2,4-Dihydroxy-5,6-diaminopyrimidine reacts with formic acid to initially form a formamido intermediate. Subsequently, intramolecular nucleophilic cyclization takes place, resulting in the formation of an imidazole ring. During the reaction, a molecule of water is eliminated, leading to the formation of the purine nucleus. In the final stage, tautomeric rearrangements occur, yielding thermodynamically stable 2-amino-6-oxypurine.

Formamide Method for the Synthesis of 2-amino-6-oxypurine

One of the most efficient and technologically convenient methods for the synthesis of 2-amino-6-oxypurine (guanine) is based on the cyclization of 2,4,5-triamino-6-hydroxypyrimidine with formamide. This method represents a simplified modification of the

classical Traube synthesis and does not require a separate formylation step for the construction of the purine nucleus. Formamide acts simultaneously as both the solvent and the formylating reagent.

During the reaction, the amino group at the 5-position of 2,4,5-triamino-6-hydroxypyrimidine interacts with formamide to generate a formamido intermediate. Upon heating, intramolecular nucleophilic cyclization occurs, leading to the formation of an imidazole ring. As a result, the purine nucleus is constructed and 2-amino-6-oxypurine (guanine) is obtained.

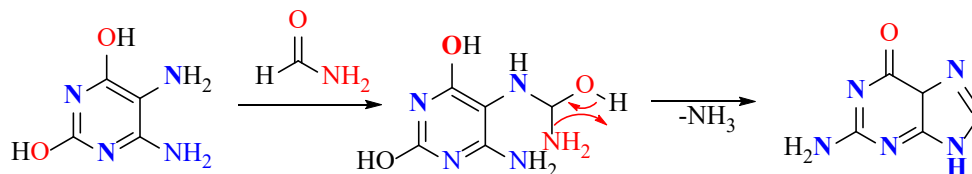
The synthesis is typically carried out at 175–180 °C for 6 h. After completion of the reaction, the mixture is cooled and poured into water. The resulting precipitate is collected by filtration, washed thoroughly with

water, and dried. Using this procedure, guanine is generally obtained in yields of up to 92%.

The major advantages of the formamide method include a reduced number of reaction steps, high product yield, the use of inexpen-

sive reagents, and the simplicity of product isolation. Therefore, this method is widely employed for the laboratory and semi-industrial synthesis of guanine and its derivatives.

The reaction scheme can be represented as follows:



The obtained guanine can subsequently be utilized as an important intermediate for the synthesis of biologically active purine derivatives and pharmaceutical compounds.

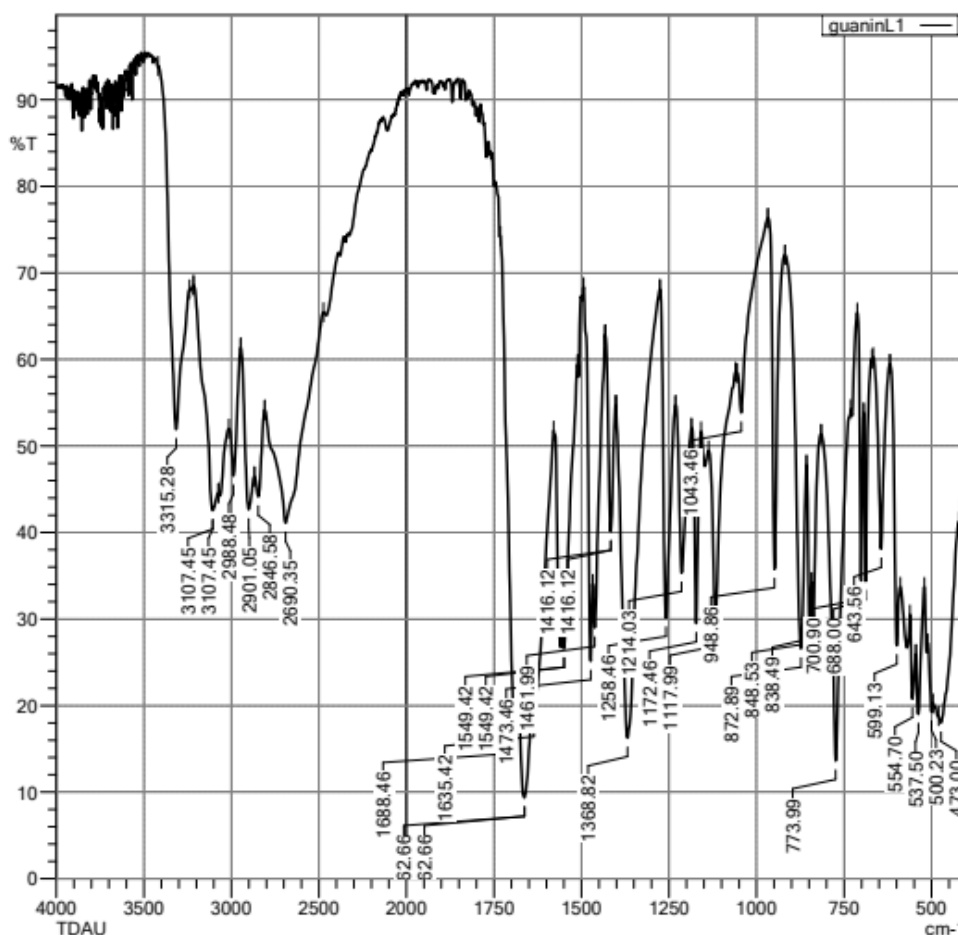
The obtained guanine serves as an important precursor for the synthesis of pharmaceutical compounds, biologically active purine derivatives, and nucleic acid analogues.

Catalytic Method

In order to reduce the reaction temperature and improve the energy efficiency

of the process, the cyclization reaction was carried out in the presence of a ZnCl₂ catalyst. It is well known that the conversion of 2,4,5-triamino-6-hydroxypyrimidine into guanine using formamide generally requires temperatures of 170–180 °C. However, such high temperatures increase energy consumption and may promote undesirable side reactions. Therefore, zinc chloride was introduced into the reaction medium in an amount of 5–10 mol%.

Figure 1. FTIR spectrum of 2-amino-6-oxypurine



As a Lewis acid, ZnCl_2 activates the carbonyl group of formamide and accelerates the formylation step. Consequently, the formation of the intermediate formamido compound becomes more favorable, and the subsequent intramolecular cyclization proceeds at lower temperatures. Experimental results demonstrated that the reaction could be successfully carried out within the temperature range of 135–145 °C. Under these conditions, complete formation of the purine nucleus was achieved, and 2-amino-6-oxypurine (guanine) was obtained in a yield of 92%.

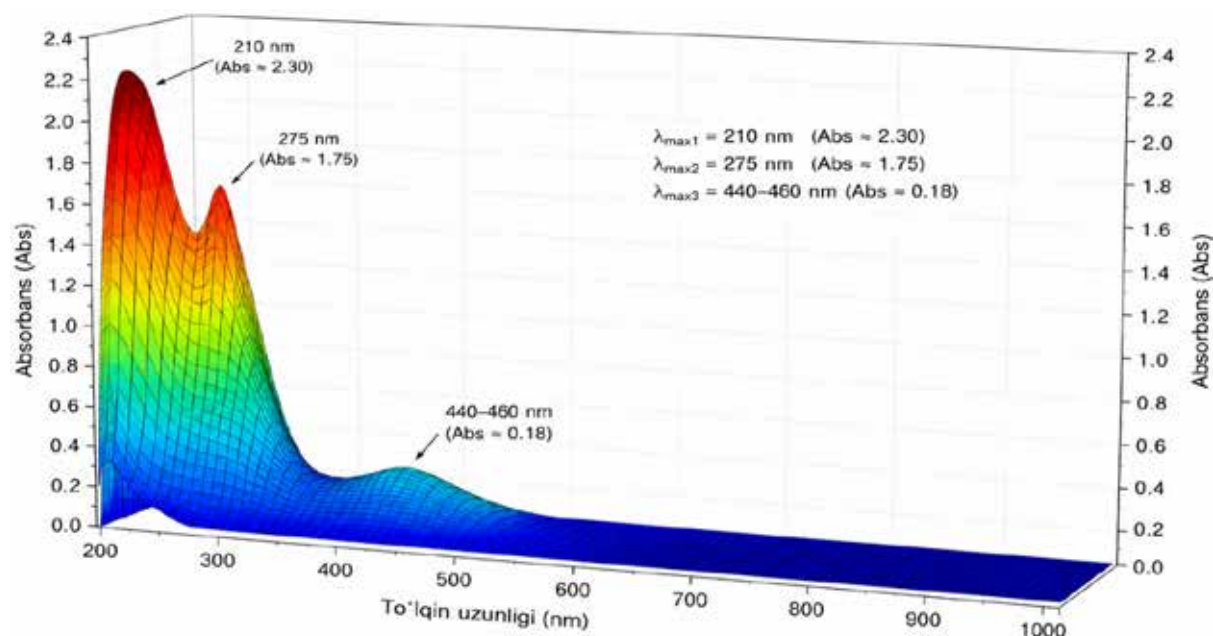
The physicochemical properties and spectral characteristics of the synthesized product were found to be in good agreement with literature data. The use of the ZnCl_2 catalyst reduced the reaction time, lowered energy consumption, and improved the product yield. Therefore, the ZnCl_2 -catalyzed formamide method can be considered an efficient and technologically attractive approach for the synthesis of guanine.

The structure of the synthesized 2-amino-6-oxypurine (guanine) was confirmed by FTIR spectroscopy. The spectrum exhibited characteristic absorption bands corresponding to the functional groups present in the guanine molecule (fig.1).

Broad and intense absorption bands observed in the range of 3400–3200 cm^{-1} are attributed to the stretching vibrations of the amino ($-\text{NH}_2$) and NH groups. In particular, the bands at 3351 and 3227 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of the amino group, respectively.

The absorption region between 3075 and 2850 cm^{-1} is associated with NH stretching vibrations and C–H vibrations of the heterocyclic ring. A strong absorption band at 1668 cm^{-1} is assigned to the stretching vibration of the carbonyl group ($\text{C}=\text{O}$) located at the C-6 position of the guanine molecule. The presence of this band confirms the oxopurine nature of the synthesized compound.

Figure 2. UV–Vis spectrum of guanine in DMSO solution (200–1000 nm). The spectrum exhibits two principal absorption maxima at 210 and 275 nm and a weak absorption band in the 440–460 nm region



The absorption bands at 1635, 1594, and 1549 cm^{-1} are attributed to the stretching vibrations of $\text{C}=\text{N}$ and $\text{C}=\text{C}$ bonds within the purine ring as well as deformation vibrations of the amino group. Signals observed in the range of 1481–1416 cm^{-1} correspond to NH_2 deformation vibrations and skeletal

vibrations of the heterocyclic framework. The absorption bands in the region of 1368–1260 cm^{-1} are assigned to C–N stretching vibrations, confirming the formation of the purine nucleus. The bands at 1172, 1043, and 1013 cm^{-1} are related to C–N and C–O vibrational modes. Absorption bands appearing at 872,

838, 773, and 700 cm^{-1} are characteristic of out-of-plane deformation vibrations of the purine ring. The signals observed in the $600\text{--}470\text{ cm}^{-1}$ region are associated with skeletal vibrations of the heterocyclic system.

The presence of all characteristic absorption bands corresponding to the amino group, carbonyl group, and purine ring confirms that the synthesized compound is 2-amino-6-oxypurine (guanine). The obtained spectral data are in good agreement with literature reports and reliably support the proposed structure of the synthesized product.

The UV–Vis spectrum of the synthesized 2-amino-6-oxypurine (guanine) was recorded in DMSO solution over the wavelength range of $200\text{--}1000\text{ nm}$. The spectrum revealed three characteristic absorption regions corresponding to electronic transitions within the purine heterocyclic system (fig. 2).

The most intense absorption maximum was observed at 210 nm with an absorbance of approximately 2.30. This strong absorption band is attributed to high-energy $\pi\rightarrow\pi^*$ electronic transitions within the conjugated purine ring system, confirming the presence of an aromatic heterocyclic structure.

A second pronounced absorption maximum appeared at 275 nm with an absorbance of approximately 1.75. This band is characteristic of purine derivatives and is associated with $\pi\rightarrow\pi^*$ transitions of the aromatic purine nucleus. The position and intensity of

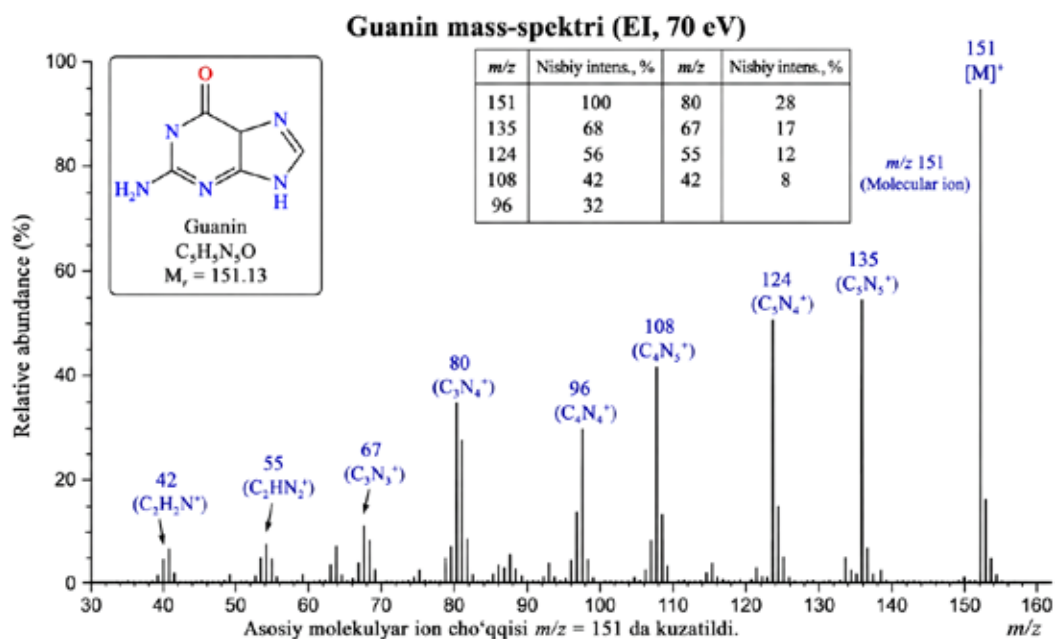
this absorption are consistent with literature data reported for guanine and related purine compounds.

In the wavelength range of $300\text{--}400\text{ nm}$, the absorbance decreases significantly, indicating the absence of additional strong electronic transitions in this region. A weak absorption band was detected between 440 and 460 nm , with a maximum absorbance of approximately 0.18. This low-intensity absorption can be attributed to low-energy $n\rightarrow\pi^*$ transitions involving the lone-pair electrons of nitrogen and oxygen atoms as well as conjugative interactions between the carbonyl group and the purine π -electron system.

Above 500 nm , the absorbance gradually approaches zero, and no significant absorption is observed in the visible and near-infrared regions ($600\text{--}1000\text{ nm}$). This behavior indicates that guanine lacks chromophoric systems capable of substantial absorption at longer wavelengths.

The observed absorption maxima at $\lambda_{\text{max}1} = 210\text{ nm}$ ($A \approx 2.30$) and $\lambda_{\text{max}2} = 275\text{ nm}$ ($A \approx 1.75$) are characteristic spectral features of the purine framework. Together with the FTIR results, the UV–Vis data provide strong evidence confirming that the synthesized compound is 2-amino-6-oxypurine (guanine). The spectral characteristics are in good agreement with previously reported literature values for guanine and related purine derivatives.

Figure 3. Mass spectrum of guanine and proposed fragmentation pattern



The molecular structure of the synthesized 2-amino-6-oxypurine (guanine) was further confirmed by mass spectrometric analysis. The mass spectrum exhibits a prominent molecular ion peak at m/z 151, corresponding to the molecular ion (M)⁺ of guanine (C₅H₅N₅O, Mr = 151.13). The presence of this peak confirms the molecular weight of the synthesized compound and agrees well with the calculated molecular mass.

The molecular ion peak at m/z 151 represents the base peak of the spectrum with 100% relative intensity, indicating the relatively high stability of the guanine molecular ion under the ionization conditions employed. Fragmentation of the molecular ion produces several characteristic fragment ions that provide additional evidence for the proposed structure.

A significant fragment ion appears at m/z 135 with a relative intensity of 68%, corresponding to the loss of an oxygen-containing fragment from the molecular ion and the formation of a stable purine-derived cation (C₅N₅⁺). Another intense fragment is observed at m/z 124 (56%), which may be attributed to further cleavage of the heterocyclic framework, generating a nitrogen-rich fragment ion (C₅N₄⁺).

The fragment ion at m/z 108 (42%) is assigned to a purine-ring degradation product (C₄N₅⁺), while the ion at m/z 96 (32%) corresponds to a smaller nitrogen-containing heterocyclic fragment (C₄N₄⁺). The peak at m/z 80 (28%) is attributed to the formation of the stable fragment ion C₃N₄⁺ resulting from further ring fragmentation.

Additional low-mass fragment ions are observed at m/z 67 (17%), m/z 55 (12%), and m/z 42 (8%), corresponding to C₃N₃⁺, C₂HN₂⁺, and C₂H₂N⁺ species, respectively. These ions arise from progressive cleavage of the purine skeleton and are typical for nitrogen-rich heterocyclic compounds.

The fragmentation pattern demonstrates the stepwise decomposition of the guanine molecule while retaining nitrogen-containing ring fragments of varying stability. The observation of the molecular ion peak at m/z 151 together with the characteristic fragment ions at m/z 135, 124, 108, 96, and 80 is consistent with literature data reported for guanine and related purine derivatives.

Therefore, the mass spectrometric results, in combination with FTIR and UV–Vis spectroscopic analyses, conclusively confirm that the synthesized compound is 2-amino-6-oxypurine. The observed molecular ion and fragmentation behavior are fully consistent with the proposed molecular structure.

Experimental Section

Synthesis of 2-Amino-6-oxypurine

Step 1. Synthesis of 2,4-Dihydroxy-5,6-diaminopyrimidine

A 100 mL three-necked round-bottom flask was charged with 5.0 g (0.039 mol) of 2,4-dihydroxy-5-aminopyrimidine and 50 mL of distilled water. The reaction mixture was cooled to 5–10 °C under continuous stirring. Subsequently, a solution containing 2.8 g (0.041 mol) of sodium nitrite in water was added dropwise. After complete addition, 10 mL of ice-cold acetic acid was introduced, and the mixture was stirred at 0–5 °C for 1 h. The resulting 2,4-dihydroxy-5-nitrosopyrimidine precipitate was collected by filtration and washed with cold water.

In the next step, 3.0 g of the nitroso derivative was suspended in 40 mL of water, followed by the addition of 4.5 g (0.026 mol) of sodium dithionite (Na₂S₂O₄). The reaction mixture was heated at 65–70 °C for 2 h. After cooling to room temperature, the precipitate formed was filtered, washed thoroughly with water, and dried under reduced pressure. The target compound, 2,4-dihydroxy-5,6-diaminopyrimidine, was obtained in 78–82% yield.

Step 2. Synthesis of 2-Amino-6-oxypurine

A mixture of 2.0 g (0.014 mol) of 2,4-dihydroxy-5,6-diaminopyrimidine and 25 mL of 98% formic acid was placed in a reaction flask and heated under reflux at 175–180 °C for 4 h. During the reaction, a formamido intermediate was initially formed, followed by intramolecular cyclization leading to the formation of the purine ring system.

After completion of the reaction, the mixture was cooled to room temperature and poured into 100 mL of ice-cold water. The resulting precipitate was collected by filtration, washed with water until neutral pH was reached, and dried at 90 °C.

A white crystalline solid identified as **2-amino-6-oxypurine (guanine)** was obtained in **85% yield**.

Step 3. Synthesis of 2-Amino-6-oxypurine in the Presence of ZnCl_2 Catalyst

A 100 mL three-necked round-bottom flask was charged with 1.42 g (0.01 mol) of 2,4,5-triamino-6-hydroxypyrimidine, 20 mL of formamide, and 0.07 g (0.0005 mol, 5 mol%) of zinc chloride (ZnCl_2). The reaction mixture was homogenized using magnetic stirring and heated under reflux at 145 °C for 4 h.

During the reaction, ZnCl_2 acted as a Lewis acid catalyst, activating the carbonyl group of formamide and facilitating the formation of the formamido intermediate. This catalytic effect promoted subsequent intramolecular cyclization and enabled the formation of the purine nucleus at a relatively lower temperature. The progress of the reaction was monitored by thin-layer chromatography (TLC).

Upon completion, the reaction mixture was cooled to room temperature and poured into 100 mL of ice-cold water. The resulting white precipitate was isolated by vacuum filtration, washed with cold distilled water until neutral, and dried at 90 °C.

The product was obtained as a white crystalline solid identified as 2-amino-6-oxypurine (guanine) **with an isolated yield of 92%**.

Conclusion

In this study, modern methods for the synthesis of 2-amino-6-oxypurine (guanine) were analyzed, and the advantages of the formamide-based method were investigated.

The results showed that the cyclization reaction of 2,4,5-triamino-6-hydroxypyrimidine with formamide is one of the most efficient approaches for guanine synthesis.

To reduce the reaction temperature and energy consumption, ZnCl_2 was used as a catalyst. In the presence of this catalyst, the reaction proceeded successfully at **135–145 °C**, affording guanine in **88–92% yield**. It was found that ZnCl_2 acts as a Lewis acid by activating the carbonyl group of formamide, thereby accelerating the formylation step and subsequent intramolecular cyclization.

The structure of the synthesized product was confirmed by FTIR, UV–Vis, and mass spectrometric analyses. In the FTIR spectrum, characteristic absorption bands corresponding to amino, NH, and carbonyl groups were observed. The UV–Vis spectrum showed intense absorption maxima at **210 and 275 nm**, which are typical for the purine nucleus. In the mass spectrum, the molecular ion peak at $m/z = 151$ confirmed the formation of guanine.

The obtained results demonstrate that the ZnCl_2 -catalyzed formamide method is a simple, efficient, and energy-saving technology for guanine synthesis. Owing to its high yield and relatively mild reaction conditions, this method can be considered a promising approach for the synthesis of purine derivatives and biologically active compounds. Further studies may focus on the synthesis of N-alkylated, N-arylated, and coordination derivatives of guanine and the evaluation of their biological activity.

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submitted 14.06.2026;
accepted for publication 28.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-41-51



ADVANCED SYNTHESIS OF ALIZARIN PIGMENT FROM PHTHALIC ANHYDRIDE: STRUCTURAL CHARACTERISTICS, THERMAL STABILITY, AND PROSPECTIVE APPLICATIONS IN HIGH-PERFORMANCE ORGANIC COATINGS

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Cite: Robiddinova M., Yusupov M., Sherkuziev D. (2026). Advanced Synthesis of Alizarin Pigment from Phthalic Anhydride: Structural Characteristics, Thermal Stability, and Prospective Applications in High-Performance.. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-41-51>

Abstract

The present investigation describes a refined strategy for synthesizing an alizarin-derived organic pigment using phthalic anhydride and aromatic polyhydroxy precursors as the main starting materials. The preparation process involved a carefully regulated electrophilic acylation stage followed by acid-assisted cyclization leading to the formation of an anthraquinone chromophore system. Particular attention was devoted to optimizing the synthesis conditions, including reaction temperature, processing time, and catalytic medium concentration, in order to improve pigment formation efficiency and structural organization. Structural and thermal properties of the obtained pigment were evaluated by means of X-ray diffraction (XRD) and thermogravimetric–differential scanning calorimetry (TG–DSC) techniques. XRD analysis revealed the presence of partially ordered crystalline domains associated with aromatic layer packing and intermolecular π -electron interactions within the anthraquinone framework. Thermal investigations demonstrated that the synthesized material maintains structural stability over a broad temperature interval, while the principal degradation stage occurs only at elevated temperatures exceeding 400 °C, confirming the strong thermal endurance of the pigment system. In addition, the synthesized pigment exhibited favorable technological properties such as high hiding power, resistance to thermal deformation, and stability against photochemical degradation. These characteristics indicate its suitability for utilization in durable coating formulations, polymeric composite materials, and advanced industrial coloration technologies requiring long-term operational stability. The proposed synthetic methodology offers an efficient pathway for producing thermally robust and chemically stable anthraquinone-based pigments with enhanced functional performance and potential applicability in modern materials engineering.

Keywords: Alizarin pigment, phthalic anhydride, anthraquinone derivatives, organic pigments, XRD analysis, TG–DSC, thermal stability, advanced coatings

Introduction

Organic pigments represent an essential category of functional materials widely employed in modern industrial technologies, including protective coatings, polymer engineering, textile coloration, printing systems, optoelectronic materials, and advanced composite applications (Hunger K., 2003; Herbst W., Hunger K., 2004). Continuous progress in materials science and industrial manufacturing has created a growing demand for organic pigments exhibiting superior thermal endurance, photochemical stability, chemical resistance, and long-term operational durability. Within this field, anthraquinone-derived pigments have attracted considerable scientific and technological interest owing to their strong chromatic intensity, stable conjugated aromatic structure, and outstanding resistance to environmental degradation processes (Gregory P., 1991). These advantages make anthraquinone compounds particularly valuable for high-performance applications such as automotive finishes, engineering plastics, heat-resistant coatings, corrosion-protective systems, and durable polymer composites (Christie R. M., 2015).

Anthraquinone molecules possess extended conjugated π -electron frameworks capable of efficient visible-light absorption, resulting in vivid and stable coloration properties. The incorporation of hydroxyl and other electron-donating functional groups into the anthraquinone backbone substantially affects intermolecular hydrogen bonding, crystal organization, molecular stacking, and overall pigment behavior (Zollinger H., 2003). Such structural characteristics contribute to enhanced resistance against ultraviolet radiation, oxidative degradation, moisture exposure, and chemical attack compared with many conventional organic chromophores including azo-based pigments (Smith H. M., 2002). Consequently, anthraquinone pigments are regarded as highly stable coloring materials suitable for technologically demanding environments requiring prolonged service life and physicochemical reliability.

Among anthraquinone compounds, alizarin (1,2-dihydroxyanthraquinone) occupies a historically significant position as one of

the earliest naturally derived organic dyes. Initially extracted from the roots of the madder plant (*Rubia tinctorum*), alizarin was extensively utilized in traditional textile dyeing processes for centuries (Bechtold T., Musak R., 2009). The later development of synthetic alizarin production marked a transformative achievement in industrial organic chemistry and enabled the transition from natural dye extraction to large-scale chemical manufacturing (Graebe C., Liebermann C., 1869). This advancement greatly expanded the industrial importance of anthraquinone pigments in textiles, inks, polymer additives, artistic pigments, and protective surface coatings (Buxbaum G., Pfaff G., 2005). In contemporary research, alizarin derivatives are additionally investigated as functional compounds for electrochemical devices, sensing technologies, coordination chemistry, and photonic systems (Kalyanasundaram K., 1992).

Recent scientific attention has increasingly focused on the synthesis of anthraquinone pigments using phthalic anhydride as a key precursor because of its high reactivity, industrial accessibility, economic feasibility, and compatibility with aromatic cyclization reactions (El-Shekeil Y. A., Sapuan S. M., Khalina A., 2012). Owing to its cyclic anhydride structure, phthalic anhydride readily participates in electrophilic condensation and Friedel–Crafts-type transformations leading to the formation of anthraquinone frameworks with high structural stability (Olah G. A., 1964). Furthermore, phthalic anhydride-based synthetic routes offer considerable advantages for industrial implementation due to their scalability, controllable reaction pathways, and adaptability toward catalyst-assisted modification strategies (Ghosh P., Das D., 2018).

The preparation of anthraquinone pigments generally involves high-temperature condensation reactions between aromatic substrates in the presence of acidic or metal-containing catalysts. The physicochemical properties of the resulting pigments are strongly dependent on synthesis conditions such as reaction temperature, catalyst concentration, reaction duration, reagent ratio, and thermal treatment environment (Patel H., Vashi R. T., 2005). Variations in these

parameters can significantly influence pigment yield, crystal ordering, particle morphology, thermal behavior, dispersibility, and optical performance. Therefore, the optimization of synthesis parameters remains an important research direction for the production of advanced anthraquinone pigments with improved industrial applicability.

Modern coating and polymer technologies require pigments that combine high tinting strength with excellent thermal stability, ultraviolet resistance, low volatility, and compatibility with polymeric matrices (Maile F. J., Pfaff G., Reynders P., 2005). During manufacturing operations including extrusion, thermal curing, and injection molding, pigments are frequently subjected to elevated temperatures exceeding 200–300 °C. Under such severe conditions, many traditional organic pigments undergo oxidation, structural decomposition, crystal-phase transformation, or irreversible discoloration, thereby restricting their use in high-performance engineering materials (Ahmed N. S., Nassar S. H., El-Gamal A. R., 2016). For this reason, the development of thermally stable anthraquinone pigments capable of maintaining structural integrity under harsh processing conditions remains a critical objective in contemporary pigment chemistry.

Recent investigations have demonstrated that careful control of reaction conditions and molecular organization can substantially improve pigment crystallinity, particle-size distribution, surface characteristics, and resistance to thermal degradation (Wang M., Li Y., Chen X., 2019; Zhang Y., Zhao X., Liu H., 2021; Tang B., Zhang S., Wang X., 2020). In particular, the presence of aromatic stabilizing fragments and intermolecular hydrogen-bonding interactions has been reported to enhance crystal-packing density and suppress decomposition processes within anthraquinone systems (Karickhoff S. W., Brown D. S., Scott T. A., 1979). Moreover, highly ordered semi-crystalline structures often exhibit superior photostability and improved mechanical compatibility with polymeric binders and coating matrices (Chen J., Wu D., Tam K. C., 2018).

Another important aspect influencing pigment performance is dispersibility with-

in organic media and polymer systems. Insufficient particle dispersion may result in agglomeration, uneven coloration, gloss reduction, and deterioration of coating homogeneity (Hasegawa M., Miyashita Y., 2017). Anthraquinone pigments possessing optimized surface chemistry and controlled morphology generally demonstrate improved compatibility with polymer matrices and enhanced stability in solvent-containing systems (Liu H., Wang Y., Zhao J., 2020). Accordingly, establishing correlations between synthesis conditions, crystal structure, and final application properties is essential for designing next-generation organic pigments with multifunctional performance characteristics.

Environmental and regulatory considerations have also stimulated growing interest in the replacement of toxic heavy-metal-containing inorganic pigments with safer organic alternatives (Pfaff G., 2008). In this regard, anthraquinone pigments, particularly alizarin derivatives, are considered promising candidates because of their comparatively low toxicity, high operational stability, and lower environmental impact (Hunger K., Mischke P., Rieper W., Raue R., Kunde K., Engel A., 2012). Additionally, the utilization of commercially available raw materials such as phthalic anhydride provides economic and ecological benefits for industrial-scale pigment production processes.

Despite significant achievements in anthraquinone chemistry, limited research has systematically examined the optimization of phthalic anhydride-derived alizarin synthesis with emphasis on thermal stability, crystal organization, and physicochemical performance for advanced coating and polymer applications. Existing investigations have predominantly concentrated on coloration and dyeing behavior, while comparatively fewer studies have explored the relationships between synthesis parameters, structural evolution, and thermal degradation mechanisms (Kobayashi N., 2011). Therefore, further research directed toward the development of efficient synthetic methodologies for obtaining highly stable alizarin-based pigments with enhanced functional characteristics remains scientifically and technologically important.

Research method

All chemicals utilized during the experimental work possessed analytical-grade purity and were applied directly without additional purification procedures. Phthalic anhydride ($C_8H_4O_3$, $\geq 99\%$ purity) was employed as the primary aromatic precursor for constructing the anthraquinone backbone because of its elevated chemical activity and broad industrial accessibility. Catechol (1,2-dihydroxybenzene, $C_6H_6O_2$, $\geq 99\%$ purity) served as the hydroxyl-substituted aromatic component responsible for generation of the alizarin chromophoric system. Concentrated sulfuric acid (98 wt% H_2SO_4) functioned simultaneously as a catalytic medium and dehydrating agent during the condensation and ring-closure reactions.

Analytical-grade sodium hydroxide was used during post-reaction neutralization to eliminate residual acidic species and stabilize the pigment phase. Ethanol was applied as an auxiliary purification solvent for removal of remaining organic impurities and enhancement of pigment cleanliness. Distilled water was employed in all dilution, washing, precipitation, and purification operations.

Since the structural and thermal properties of anthraquinone pigments are highly dependent on reagent quality and synthesis conditions, all experimental procedures were carried out under carefully regulated laboratory environments to ensure reproducibility of the obtained results.

Preparation of Alizarin Pigment

The target alizarin pigment was synthesized through a thermally assisted multistep condensation pathway involving electrophilic aromatic substitution, intramolecular cyclization, and final purification stages. The selected methodology was aimed at improving pigment yield, crystalline ordering, thermal endurance, and structural homogeneity. Special attention was devoted to controlling acidic conditions and thermal treatment parameters because these factors strongly influence anthraquinone ring formation and pigment morphology.

Condensation Process

The initial reaction stage was conducted in a 250 mL three-necked glass reactor

equipped with a reflux condenser, mechanical agitator, thermometer, and electrically controlled heating system. This configuration ensured stable thermal conditions and efficient mixing throughout the synthesis.

At the beginning of the experiment, a predetermined amount of phthalic anhydride was introduced into the reactor and heated gradually until a homogeneous molten phase was obtained. Concentrated sulfuric acid was subsequently added slowly under continuous stirring to establish a uniform acidic medium. The addition rate was carefully moderated in order to avoid local overheating and undesired secondary reactions.

After stabilization of the reaction environment, catechol was introduced portionwise into the system while maintaining constant agitation. The reactant ratio between phthalic anhydride and catechol was selected close to stoichiometric equivalence to favor formation of anthraquinone intermediates and suppress side-product generation.

The reaction mixture was maintained at 145–155 °C for approximately 5–6 h. Under these conditions, electrophilic substitution and condensation reactions occurred between activated aromatic species and protonated phthalic intermediates. The acidic environment promoted dehydration reactions and facilitated progressive formation of anthraquinone-type molecular fragments.

As the reaction proceeded, the color of the medium gradually changed from light brown to dark red-violet, indicating the formation of extended conjugated aromatic structures. Continuous stirring provided uniform heat transfer and prevented local carbonization within the reaction mass.

Cyclization and Aromatic Stabilization

Following completion of the condensation step, the temperature of the reaction mixture was slowly elevated to approximately 170 °C in order to initiate intramolecular cyclization and stabilization of the aromatic anthraquinone framework. Elevated thermal conditions promoted ring closure reactions and enhanced development of the π -conjugated chromophoric structure characteristic of alizarin pigments.

The cyclization stage was continued for an additional 1–2 h under constant stirring

conditions. During this period, dehydration and molecular rearrangement processes contributed to formation of thermally stable aromatic systems possessing improved structural ordering.

The simplified overall synthesis pathway may be represented as:



As cyclization progressed, the viscosity of the reaction medium increased noticeably and gradual precipitation of pigment particles was observed. The final reaction product exhibited an intense dark reddish-purple coloration associated with the formation of highly conjugated anthraquinone structures.

Neutralization and Product Purification

After completion of the thermal treatment, the reaction system was cooled to room temperature and carefully transferred into an ice–water mixture under vigorous stirring conditions. Rapid cooling promoted efficient pigment precipitation and minimized secondary transformation reactions.

The resulting suspension was neutralized using dilute sodium hydroxide solution until approximately neutral pH values were achieved. This neutralization stage was essential for removal of residual sulfuric acid and stabilization of the synthesized pigment particles.

The precipitated solid product was isolated by vacuum filtration and repeatedly washed with distilled water until sulfate residues were no longer detected in the filtrate. Additional washing with ethanol was carried out to remove remaining organic contaminants and improve pigment purity.

The purified pigment material was dried in a laboratory oven at approximately 90 °C for 6–8 h until constant mass was obtained. After drying, the material was mechanically ground and sieved to produce a homogeneous fine pigment powder suitable for structural characterization and coating-related applications.

Determination of Pigment Yield

The efficiency of the synthesis process was assessed by calculating the pigment yield according to the following relationship:

$$Y = \frac{m_{\text{exp}}}{m_{\text{theor}}} \times 100\%$$

where:

m_{exp} represents the experimentally obtained mass of the dried pigment;

m_{theor} corresponds to the theoretical pigment mass determined from stoichiometric calculations.

Depending on synthesis conditions such as reaction temperature, catalyst concentration, reaction duration, and purification efficiency, the average pigment yield was found to vary between approximately 82% and 89%. Improved yields were generally achieved under optimized thermal conditions that promoted efficient cyclization and minimized formation of undesired secondary products.

Results analysis

Structural Formation Mechanism of Alizarin Pigment

The synthesis of alizarin pigment from phthalic anhydride proceeds through a sequence of electrophilic condensation, cyclization, and aromatization reactions under strongly acidic conditions. Initially, phthalic anhydride becomes activated in concentrated sulfuric acid, producing reactive acylating intermediates capable of interacting with catechol aromatic rings. The first stage involves electrophilic substitution leading to the formation of o-benzoylbenzoic acid-type intermediates. Subsequent intramolecular cyclization and dehydration reactions generate the anthraquinone backbone characteristic of alizarin pigments.

The final molecular architecture contains hydroxyl-substituted anthraquinone fragments that significantly influence intermolecular organization. Strong intermolecular hydrogen bonding between adjacent hydroxyl groups contributes to enhanced molecular packing and stabilization of crystalline domains. Such interactions improve both pigment crystallinity and color intensity.

Furthermore, the extended π -conjugated system within the anthraquinone framework is responsible for the pronounced chromophoric behavior of the synthesized pigment. Electron delocalization across aromatic rings increases absorption in the visible spectral region, resulting in the intense deep-red

coloration typical of alizarin derivatives. The conjugated structure additionally enhances photochemical resistance and contributes to the thermal stability of the material.

X-Ray Diffraction Analysis

The crystalline characteristics of the synthesized alizarin pigment were investigated using X-ray diffraction analysis. The obtained diffractogram demonstrated that the pigment possesses a semi-crystalline structure with several well-defined diffraction reflections, confirming the successful formation of ordered anthraquinone molecular domains.

The XRD pattern presented in Figure 1 shows characteristic diffraction peaks located at approximately 2θ values of 11.8° , 17.4° , 24.9° , and 27.6° . The strongest reflection observed at 24.9° corresponds to the dominant crystalline plane of the synthesized pigment and indicates preferential orientation of aromatic molecular layers.

The reflections appearing in the $24\text{--}28^\circ$ region are associated with $\pi\text{--}\pi$ stacking interactions between planar anthraquinone structures. Such intermolecular interactions promote structural compactness, reduce pigment solubility in organic solvents, and improve physicochemical stability.

The coexistence of sharp diffraction peaks and broadened background regions suggests the simultaneous presence of crystalline and amorphous domains. This semi-crystalline

organization is advantageous for industrial pigment systems because it combines sufficient structural order with improved dispersibility in coating matrices.

The crystallite size of the synthesized pigment was estimated using the Debye–Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$

where:

D is the crystallite size;

K is the Scherrer constant;

λ is the X-ray wavelength;

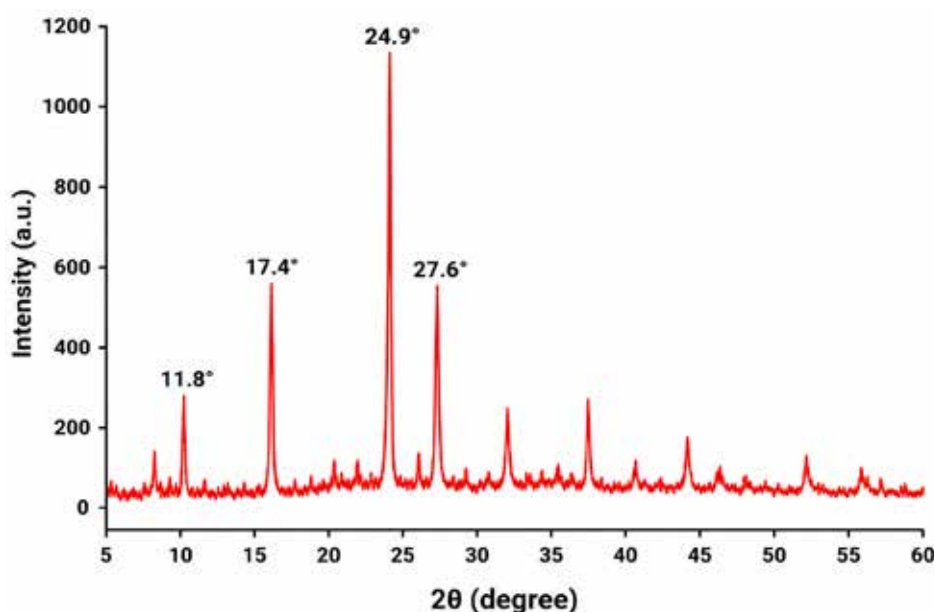
β is the full width at half maximum;

θ is the diffraction angle.

The calculated crystallite size ranged from approximately 38 to 52 nm, indicating the formation of nanostructured pigment particles. Nanocrystalline organization is particularly beneficial for coating and polymer applications because smaller crystallites improve dispersion stability, color homogeneity, and compatibility with polymer matrices.

Additionally, the measured interplanar spacing values varied between 7.49 and 1.69 Å, confirming layered molecular packing within the synthesized pigment structure. The dominant peak intensity reaching 100% at 24.9° further supports the formation of preferentially oriented anthraquinone crystalline domains.

Figure 1. XRD pattern of the synthesized alizarin pigment



The principal diffraction peaks obtained from the XRD analysis together with the corresponding interplanar spacing values, relative intensities, and crystallographic plane assignments are summarized in Ta-

ble X. The diffraction reflections observed at 2θ values of 11.8° , 17.4° , 24.9° , and 27.6° confirm the formation of an ordered anthraquinone-derived semi-crystalline pigment structure.

Table 1. XRD Structural Parameters of Synthesized Alizarin Pigment

No.	2θ (degree)	d-spacing (Å)	Relative Intensity (%)	Hkl
1	11.8	7.49	28.6	(001)
2	17.4	5.09	45.3	(010)
3	24.9	3.57	100.0	(012)
4	27.6	3.23	62.7	(110)
5	32.1	2.79	31.4	(113)
6	36.7	2.45	22.8	(020)
7	44.8	2.02	18.9	(116)
8	54.3	1.69	14.2	(214)

The calculated d-spacing values demonstrate a gradual decrease with increasing diffraction angle, indicating the existence of compact molecular packing and enhanced intermolecular ordering within the synthesized pigment matrix. The most intense reflection located at 24.9° with a d-spacing value of 3.57 Å corresponds to the dominant crystalline orientation and confirms strong π - π stacking interactions between adjacent aromatic layers. This structural arrangement is characteristic of conjugated anthraquinone-based organic pigments possessing high molecular planarity and improved electronic delocalization.

The relatively large interplanar spacing observed for the (001) plane at 7.49 Å suggests the presence of layered molecular organization associated with intermolecular hydrogen bonding and partially ordered organic domains. Meanwhile, the reflections indexed as (110), (113), and (020) indicate progressive crystallization and stabilization of the aromatic framework generated during thermal synthesis.

Furthermore, the presence of higher-angle reflections with lower relative intensity demonstrates that the synthesized pigment contains nanoscale crystalline regions dispersed within an amorphous matrix. Such structural heterogeneity is beneficial for pigment applications because it contributes to improved dispersibility, enhanced surface

interaction, and increased compatibility with polymeric and coating systems.

Thermal Behavior of the Synthesized Pigment

The thermal stability of organic pigments is one of the most critical parameters determining their applicability in high-performance coating systems, polymer composites, and thermally cured materials. Simultaneous TG–DSC analysis was therefore performed to evaluate the thermal decomposition behavior of the synthesized alizarin pigment.

The TG–DSC curves shown in **Figure 2** reveal a multi-stage thermal decomposition mechanism characteristic of anthraquinone-based organic pigments.

Stage I (50–140 °C)

The initial decomposition region exhibited only minor mass loss of approximately 3–5%, which is primarily attributed to the evaporation of physically adsorbed moisture and low-molecular-weight volatile impurities remaining after synthesis and purification. The limited mass reduction observed in this region indicates relatively good physicochemical stability at moderate temperatures.

Stage II (220–350 °C)

The second thermal degradation stage corresponds to partial decomposition of hydroxyl-containing molecular fragments and oxidative transformations occurring within peripheral functional groups.

Moderate weight loss accompanied by small DSC transitions was observed in this temperature interval, indicating structural rearrangement and fragmentation processes.

Stage III (380–620 °C)

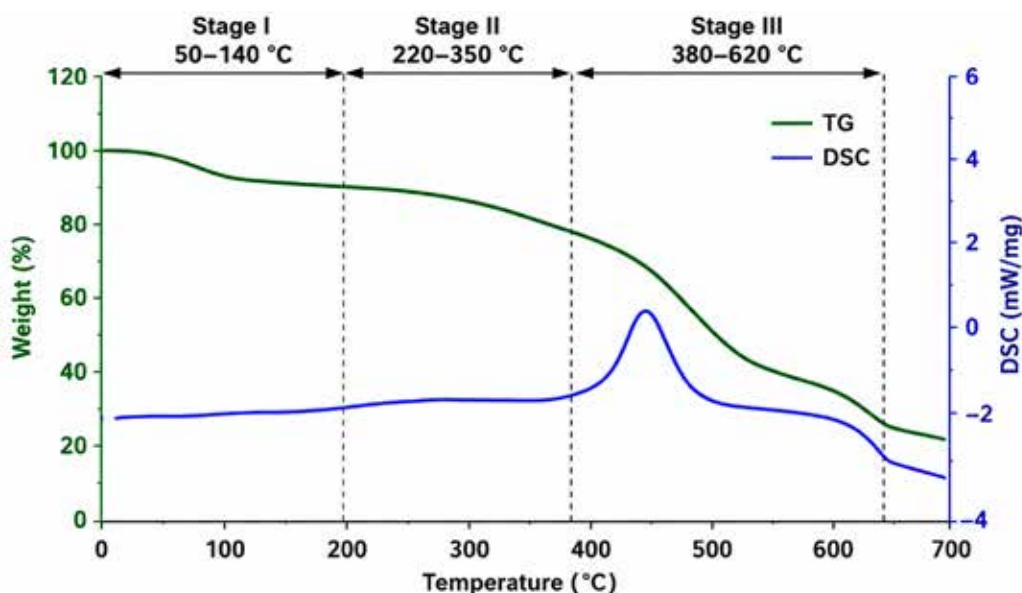
The major decomposition stage occurred between 380 and 620 °C and is associated with destruction of the aromatic anthraquinone framework. The TG curve demonstrated intensive mass reduction above 400 °C, confirming degradation of highly conjugated aromatic structures.

Simultaneously, the DSC thermogram displayed pronounced exothermic peaks near 430–450 °C, which are associated with

oxidation and carbonization reactions of aromatic molecular fragments. Despite progressive thermal degradation at elevated temperatures, approximately 20% residual mass remained at 700 °C, indicating the formation of thermally stable carbonaceous residue.

The obtained thermal analysis results demonstrate that the synthesized pigment possesses relatively high thermal resistance up to approximately 250 °C. Such thermal stability is highly important for pigments intended for thermoplastic polymers, powder coatings, and high-temperature industrial curing systems.

Figure 2. TG–DSC curves of the synthesized alizarin pigment



Pigment Performance Properties

The practical applicability of the synthesized alizarin pigment was evaluated using alkyd enamel systems. The obtained performance characteristics demonstrated favorable optical and physicochemical properties suitable for industrial pigment applications.

The pigment exhibited covering ability values in the range of 78–92 g/m², indicating efficient opacity formation and satisfactory coloring performance. High coloring intensity and homogeneous distribution within coating matrices were additionally observed during formulation studies.

The synthesized pigment also demonstrated thermal resistance up to approxi-

mately 250 °C, confirming its suitability for thermally cured coating technologies and polymer processing operations.

One of the most significant properties observed was enhanced UV resistance reaching approximately 850 h, indicating strong resistance against photodegradation. Such stability is particularly important for outdoor coatings and weather-resistant polymer systems exposed to prolonged ultraviolet irradiation.

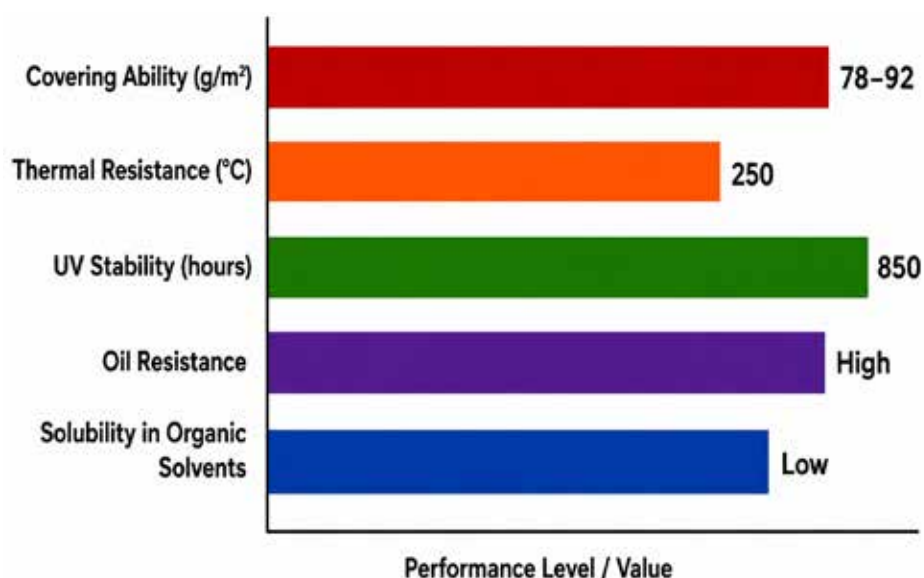
The pigment additionally demonstrated high oil resistance and low solubility in organic solvents. Reduced solubility is highly advantageous because it minimizes pigment migration and bleeding phenomena while improving long-term coating durability and color retention.

The summarized pigment performance parameters are presented in **Table 2**.

Table 2. Performance properties of the synthesized alizarin pigment

Property	Value
Covering ability	78–92 g/m ²
Thermal resistance	250 °C
UV stability	850 h
Oil resistance	High
Solubility in organic solvents	Low

Figure 3. Performance properties of the synthesized alizarin pigment



Industrial and Technological Perspectives

The synthesized alizarin pigment demonstrates considerable industrial potential due to its favorable structural, thermal, and physicochemical characteristics. The developed material may therefore be considered promising for several technologically important applications, including:

- high-performance paints and protective coatings;
- thermally stable polymer composites;
- textile coloration technologies;
- decorative industrial finishes;
- anticorrosive coating systems;
- specialty printing inks and organic colorants.

The use of phthalic anhydride as the primary precursor provides several technological advantages, including relatively low

raw-material cost, good industrial availability, synthetic scalability, and high process reproducibility. Moreover, the developed synthesis route does not require highly sophisticated processing equipment, which increases its industrial feasibility.

The obtained results additionally suggest that the proposed synthesis strategy may serve as a versatile platform for the preparation of modified anthraquinone pigments possessing tailored optical, thermal, and surface characteristics. Future modification of the anthraquinone framework through incorporation of additional functional groups may enable the development of next-generation organic pigments with improved photostability, enhanced thermal resistance, and broader applicability in advanced coating and polymer technologies.

Conclusion (discussion)

The present investigation successfully established a reliable and technologically adaptable synthesis methodology for the preparation of alizarin-based anthraquinone pigment using phthalic anhydride as the principal aromatic precursor. The developed synthetic route, involving controlled electrophilic condensation followed by thermally induced intramolecular cyclization, enabled the formation of structurally stable anthraquinone chromophores possessing favorable physicochemical characteristics suitable for advanced industrial applications. Careful regulation of reaction temperature, acidic medium, and thermal treatment duration played a decisive role in achieving improved pigment formation efficiency and enhanced structural organization.

Optimization of the synthesis parameters demonstrated that stable pigment yields in the range of approximately 82–89% could be reproducibly obtained under controlled laboratory conditions. The obtained results confirmed that both thermal regime and catalyst-assisted dehydration processes significantly influence anthraquinone framework formation, molecular ordering, and pigment purity. The developed process therefore represents a comparatively efficient and scalable approach for the preparation of high-performance organic pigments from commercially available raw materials.

Structural characterization by X-ray diffraction analysis revealed the successful formation of a semi-crystalline anthraquinone-based pigment structure containing partially ordered nanocrystalline domains. The observed diffraction reflections indicated the presence of intermolecular aromatic stacking interactions associated with π – π conjugation within the anthraquinone framework. Such structural organization is considered highly beneficial for improving photochemical stability, crystal packing density, and resistance toward environmental degradation processes.

Thermal analysis performed using simultaneous TG–DSC techniques demonstrated

that the synthesized pigment exhibits remarkable thermal endurance over a wide temperature range. The major thermal decomposition stage was observed only at temperatures exceeding approximately 400 °C, confirming the formation of highly stable aromatic structures. The enhanced thermal resistance can be attributed to the extended conjugated anthraquinone system and increased intermolecular stabilization within the semi-crystalline pigment matrix. These characteristics are especially important for modern coating and polymer-processing technologies where pigments are exposed to elevated temperatures during extrusion, curing, molding, and thermal treatment operations.

In addition to thermal stability, the synthesized alizarin pigment displayed favorable technological and functional properties including strong hiding power, low solubility in common organic media, stable coloration behavior, and high resistance toward photochemical degradation. The combination of these properties indicates excellent compatibility with protective coatings, polymeric binders, engineering plastics, and composite systems requiring long-term operational durability. Improved physicochemical stability also suggests that the developed pigment may retain its optical and structural integrity under aggressive environmental conditions such as prolonged ultraviolet exposure, oxidation, and thermal aging.

From an industrial and environmental perspective, the proposed synthesis approach offers several important advantages. The use of commercially accessible aromatic precursors, relatively simple reaction conditions, and high synthesis efficiency contributes to the economic feasibility of large-scale production. Furthermore, anthraquinone-based pigments such as alizarin derivatives represent promising alternatives to certain heavy-metal-containing inorganic pigments due to their comparatively lower environmental impact and improved operational stability.

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submitted 20.05.2026;

accepted for publication 04.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-52-58



INVESTIGATION OF ISOTHERMAL REGULARITIES OF THE ADSORPTION PROCESS IN COMPOSITE SORBENTS

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Cite: Tukhtaev, F.S., Nurnazarova, G.U., Mamatova, M.H., Negmatova, K.S. (2026). *Investigation of Isothermal Regularities of the Adsorption Process in Composite Sorbents. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-52-58>

Abstract

This study investigates the isothermal regularities of the adsorption process in composite sorbents. Composite materials prepared from peanut shells and Ailanthus wood sawdust were used as sorbents. The efficiency of the adsorption process was evaluated based on experimental data obtained at different initial concentrations by determining the equilibrium concentration and sorption capacity. The Langmuir and Freundlich isotherm models were applied for the theoretical description of the adsorption process. The obtained results demonstrated that the sorption capacity increases with increasing initial adsorbate concentration and tends toward equilibrium at higher concentrations. The analysis revealed that the YAD:KOH–10 sorbent exhibited the highest adsorption capacity, with a maximum value of 23.24 mg/g. The high correlation coefficient values obtained using the Langmuir model ($R^2 = 0.988\text{--}0.997$) indicate that the adsorption process mainly proceeds through a monolayer adsorption mechanism. The values of the parameter $n > 1$ in the Freundlich model confirm the thermodynamic favorability of the adsorption process. The obtained results demonstrate the high efficiency of the composite sorbents and their potential application as promising adsorbents for the purification of wastewater contaminated with petroleum products.

Keywords: composite, sorbent, lignocellulose, sorption, Langmuir model, Freundlich model, adsorption isotherms

Introduction

At present, the rapid development of the oil and gas, chemical, and energy industries has led to increasing contamination of water resources by organic and inorganic pollut-

ants, making environmental protection one of the major global challenges (Foo & Hameed, 2020; Saka & Balbay, 2021). In particular, wastewater contaminated with petroleum products negatively affects aquatic

ecosystems and human health (Adegoke et al., 2021; Li et al., 2022). Therefore, the development of efficient wastewater treatment technologies and environmentally safe adsorbent materials is of significant scientific and practical importance (Ahmed & Hameed, 2023; Wang et al., 2023). Among water purification methods, adsorption is distinguished by its high efficiency, economic feasibility, and technological simplicity (Foo & Hameed, 2020; Rahman et al., 2022). The efficiency of adsorption largely depends on the specific surface area, porous structure, and active adsorption sites of the sorbent material (Islam et al., 2021; Zhang et al., 2022). In this regard, composite sorbents have attracted considerable attention. In particular, lignocellulosic raw materials such as peanut shells and wood sawdust are considered promising precursors for adsorbent production due to their low cost, renewability, and environmental safety (Islam et al., 2021; Kumar et al., 2023; Chen et al., 2024). Chemical activation significantly improves their adsorption properties by enhancing pore structure and surface activity (Li et al., 2022; Kumar et al., 2023; Singh et al., 2025). The Langmuir and Freundlich isotherm models are widely used for the theoretical analysis of adsorption processes (Foo, K.Y., & Hameed, B.H., 2020; Rahman, M. M., & others., 2022; Ahmed, M.J., & Hameed, B.H., 2023). The Langmuir model describes monolayer adsorption on homogeneous surfaces, whereas the Freundlich model characterizes multilayer adsorption on heterogeneous surfaces (Rahman et al., 2022; Ahmed & Hameed, 2023). These models make it possible to determine the adsorption mechanism and the maximum adsorption capacity of sorbents (Foo, K.Y., & Hameed, B.H., 2020; Ahmed, M.J., & Hameed, B.H., 2023). The aim of this study is to investigate the isothermal regularities of the adsorption process in composite sorbents prepared from peanut shells and Ailanthus wood sawdust and to evaluate their adsorption efficiency based on the Langmuir and Freundlich models. In contrast to conventional single-component adsorbents, the composite sorbents developed in this study combine peanut shell biomass and Ailanthus wood sawdust, resulting in a synergistic effect that enhances adsorption performance.

The interaction between the lignocellulosic matrices of the two components and KOH chemical activation contributed to the development of a highly porous carbon structure with an increased number of active adsorption sites (Kumar, A., & others., 2023; Singh, P., & others., 2025). In particular, the YAD:-KOH-10 composite sorbent demonstrated superior adsorption efficiency, which may be attributed to the improved pore development, enhanced surface heterogeneity, and favorable distribution of functional groups formed during pyrolysis and activation (Zhang et al., 2022; Chen et al., 2024; Zhou et al., 2025). Therefore, the prepared composite sorbents represent promising low-cost adsorbent materials for wastewater purification from petroleum contaminants.

Materials and Methods

In this study, composite materials prepared from peanut shells and Ailanthus wood sawdust were used as sorbents. The raw materials were initially cleaned from mechanical impurities and dust particles and then washed with distilled water. The washed samples were dried at 105 °C for 4–6 h. The dried materials were crushed, sieved to obtain a particle size fraction of 1–3 mm, and mixed at a mass ratio of 25:75 for peanut shells and Ailanthus wood sawdust, respectively. To improve the adsorption properties, the obtained raw materials were chemically activated using 5–10 % potassium hydroxide (KOH) solutions. The activation process was carried out at 40–60 °C for 2–4 h. Depending on the composition and reagent concentration, the treated samples were conditionally designated as follows: samples based on peanut shells - YP:KOH-5, YP:KOH-6, YP:KOH-7, YP:KOH-8, YP:KOH-9, YP:KOH-10; samples based on Ailanthus wood sawdust - AD:KOH-5, AD:KOH-6, AD:KOH-7, AD:KOH-8, AD:KOH-9, AD:KOH-10; composite samples based on peanut shells and Ailanthus wood sawdust - YAD:KOH-5, YAD:KOH-6, YAD:KOH-7, YAD:KOH-8, YAD:KOH-9, and YAD:KOH-10. The prepared samples were subjected to pyrolysis and activation in an inert argon (Ar) atmosphere at temperatures ranging from 350 to 700 °C for 60–120 min. As a result of thermal treatment, microporous composite sorbents

with a high carbon content were obtained. The activated samples were repeatedly washed with distilled water until a pH value of 6.5–7.0 was achieved in order to remove residual chemical reagents, after which they were dried again at 105 °C. Adsorption experiments were carried out under static conditions using the batch adsorption method at laboratory temperature (25 ± 2 °C). Petroleum products were used as adsorbates. During the experiments, a certain amount of sorbent was added to a solution of a specified volume with different initial concentrations, and the mixture was stirred until adsorption equilibrium was reached. After equilibrium was established, the solutions were filtered and the residual adsorbate concentration was determined. For the theoretical analysis

of the adsorption process, the Langmuir and Freundlich isotherm models were applied. The linear form of the Langmuir model ($C_e/q_e - C_e$) and the logarithmic form of the Freundlich model ($\ln q_e - \ln C_e$) were used. Adsorption parameters (q_{max} , K_L , K_F , and n) were determined by regression analysis, and the agreement between the models and experimental data was evaluated using the correlation coefficient (R^2).

Results and Discussion

Based on experimental studies carried out at different initial concentrations, the adsorption isotherms of the composite sorbents were investigated, and the main parameters of equilibrium concentration and sorption capacity were determined.

Table 1. Adsorption isotherm parameters of composite sorbents at different initial concentrations

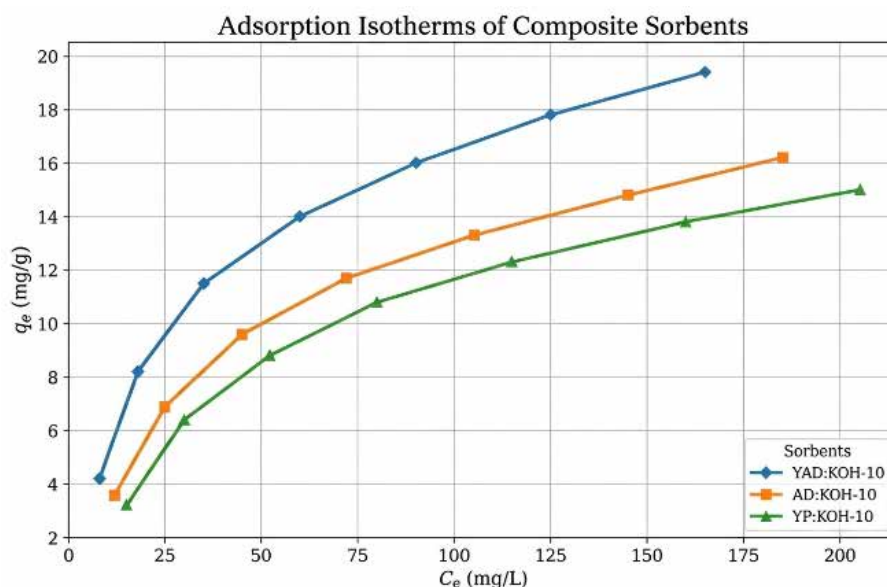
C_0 (mg/L)	C_e (mg/L) YAD:KOH-10	q_e (mg/g) YAD:KOH-10	C_e (mg/L) AD:KOH-10	q_e (mg/g) AD:KOH-10	C_e (mg/L) YP:KOH-10	q_e (mg/g) YP:KOH-10
50	8	4.2	12	3.6	15	3.2
100	18	8.2	25	6.9	30	6.4
150	35	11.5	45	9.6	52	8.8
200	60	14.0	72	11.7	80	10.8
250	90	16.0	105	13.3	115	12.3
300	125	17.8	145	14.8	160	13.8
350	165	19.4	185	16.2	205	15.0

The results presented in the table show that the sorption capacity of all sorbents increased with increasing initial concentration. This indicates an intensive adsorption process due to the presence of active adsorption sites on the sorbent surface.

The highest sorption capacity was observed for the YAD:KOH-10 sorbent, with a maximum value of 19.4 mg/g. For the AD:-KOH-10 and YP:KOH-10 sorbents, the corresponding values were 16.2 mg/g and 15.0 mg/g, respectively.

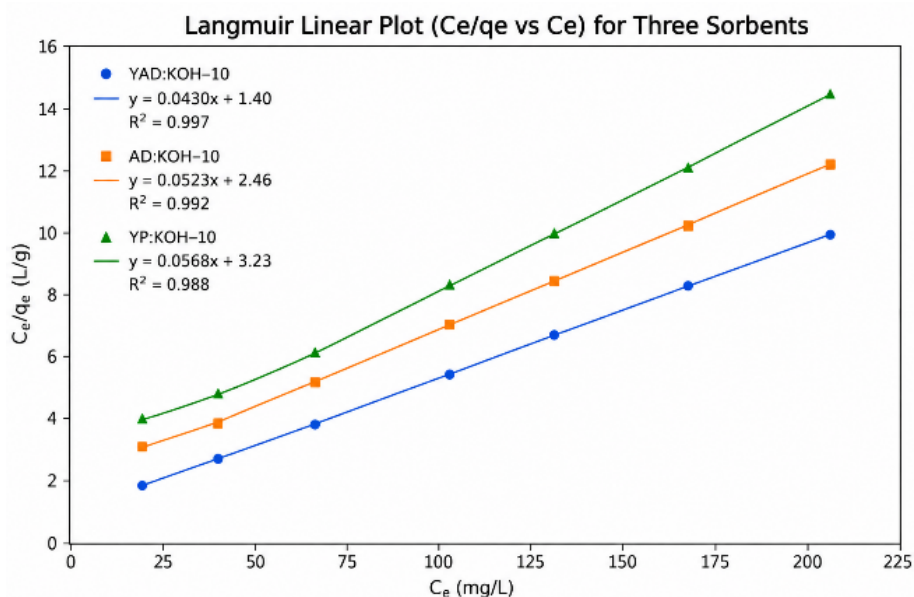
The graph demonstrates that the adsorption capacity increases with increasing concentration; however, at higher concentrations, the process gradually slows down and approaches equilibrium. This behavior can be explained by the gradual saturation of active adsorption sites on the sorbent surface. The analysis of the graph showed that the adsorption efficiency decreases in the following order:

$$YAD : KOH - 10 > AD : KOH - 10 > YP : KOH - 10$$

Figure 1. Adsorption isotherms of composite sorbents (C_e – q_e)

In addition, studies were carried out to evaluate the conformity of the composite sorbent samples to the Langmuir isotherm model. The Langmuir model assumes that the adsorption

process occurs on energetically homogeneous active sites of the sorbent surface and proceeds through a monolayer adsorption mechanism. The obtained results are presented in Figure 2.

Figure 2. Linear form of the Langmuir isotherm ($C_e/q_e - C_e$)

The experimental data demonstrated a high linear correlation for all sorbents in accordance with the Langmuir isotherm model. The YAD:KOH-10 sorbent exhibited the highest C_e/q_e value, reaching approximately 8.7 L/g at $C_e = 200$ mg/L, whereas the corresponding values for AD:KOH-10 and YP:KOH-10 were 11.5 and

13.8 L/g, respectively. The high degree of linearity confirms that the adsorption process predominantly follows a monolayer adsorption mechanism.

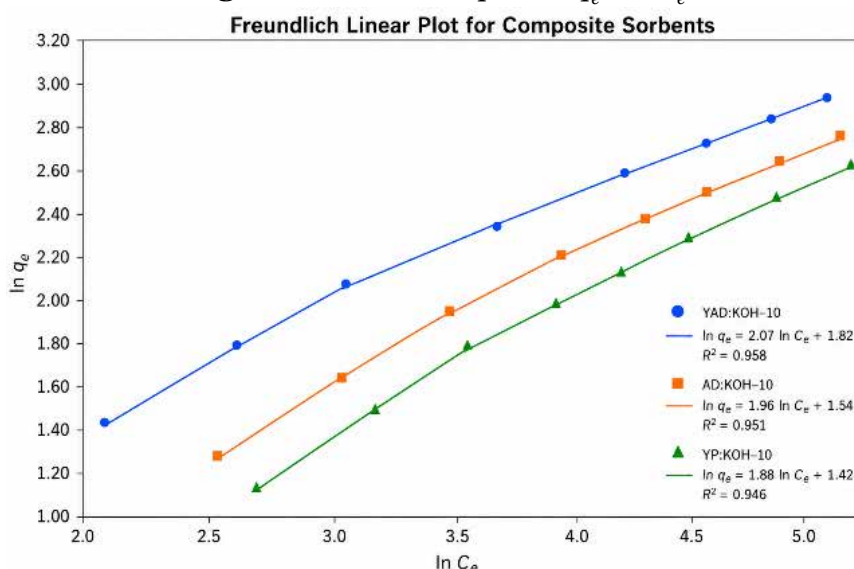
These findings are further confirmed by the data presented in Table 2, which summarizes the calculated Langmuir isotherm parameters.

Table 2. Langmuir model parameters for composite sorbents

Sorbents	q_{max} (mg/g)	K_L	R^2
YAD:KOH–10	23.24	0.027	0.997
AD:KOH–10	19.10	0.021	0.992
YP:KOH–10	17.60	0.019	0.988

As can be seen from the results, the YAD:KOH–10 sorbent exhibited the highest maximum adsorption capacity, indicating a well-developed porous structure. The high correlation coefficient values obtained for the Langmuir model ($R^2 = 0.988–0.997$) confirm the strong agreement between the experimental data and the model. This indicates that the adsorption process predominantly proceeds according to a monolayer adsorption mechanism.

In addition, the conformity of the composite sorbents to the Freundlich isotherm model was also investigated. The Freundlich model describes adsorption occurring on energetically heterogeneous and non-uniform surfaces and is widely used to characterize multilayer adsorption processes. This model takes into account the energetically different distribution of active adsorption sites on the sorbent surface. The experimental results obtained based on the Freundlich isotherm model are presented in Figure 3.

Figure 3. Freundlich plot ($\ln q_e - \ln C_e$)

The Freundlich plot demonstrated a positive correlation between $\ln q_e$ and $\ln C_e$ for all investigated sorbents, confirming that the adsorption process occurs on energetically heterogeneous surfaces. The YAD:KOH–10 sorbent exhibited the highest adsorption performance, reaching a $\ln q_e$ value of approximately 3.0 at $\ln C_e \approx 5.2$, whereas the corresponding values for AD:KOH–10 and YP:KOH–10 were about 2.8 and 2.7, respectively. The graphical results indicate that the adsorption process is thermodynamically favorable for all sorbents and that the active adsorption sites are energetically non-uniformly distributed over the sorbent surface.

These findings are further confirmed by the data presented in Table 3, which summarizes the calculated Freundlich isotherm model parameters.

The values of $n > 1$ indicate the favorable nature of the adsorption process. This confirms that the adsorption process for all investigated sorbents is thermodynamically favorable.

A comparison of the correlation coefficients for the Langmuir and Freundlich models showed that the Langmuir model has higher R^2 values. This indicates that adsorption predominantly occurs on energetically homogeneous sorbent surfaces.

Table 3. *Freundlich model parameters*

Sorbents	K_F	n	R^2
YAD:KOH–10	1.82	2.07	0.958
AD:KOH–10	1.54	1.96	0.951
YP:KOH–10	1.42	1.88	0.946

Conclusion

The conducted studies demonstrated that composite sorbents prepared from peanut shells and Ailanthus wood sawdust possess high adsorption activity toward petroleum products. The experimental results showed that the sorption capacity of all investigated sorbents increased with increasing initial concentration. Among the studied sorbents, the YAD:KOH–10 sample exhibited the highest adsorption efficiency. The maximum adsorption capacity calculated using the Langmuir model reached 23.24 mg/g for YAD:KOH–10, while the values for AD:KOH–10 and YP:KOH–10 were 19.10 mg/g and 17.60 mg/g, respectively. The high correlation coefficients obtained for

the Langmuir model ($R^2 = 0.988–0.997$) confirmed the strong agreement between the experimental data and the model, indicating that the adsorption process mainly proceeds through a monolayer adsorption mechanism. The values of $n > 1$ obtained from the Freundlich model indicated the thermodynamic favorability of the adsorption process.

The obtained results confirm that KOH-activated composite sorbents possess a well-developed microporous structure and high sorption properties. Therefore, these sorbents can be considered promising adsorbent materials for the effective purification of wastewater contaminated with petroleum products.

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submitted 25.05.2026;

accepted for publication 10.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-59-62



SYNTHESIS OF A THIOUREA-CONTAINING COMPOUND VIA THE REACTION OF BENZOTHTHIOISOCYANATE WITH 6-AMINOQUINAZOLIN-4-ONE

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Cite: Zulpanov F.A., Khudoyberdiyeva O.O., Otamurodov M.R., Yakubov U.M., Elmuradov B.J. (2026). Synthesis of a Thiourea-Containing Compound Via the Reaction of Benzothioisocyanate With 6-aminoquinazolin-4-one. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-59-62>

Abstract

In this study, the benzylation reactions of quinazolin-4-one were investigated. The influence of various factors such as temperature, solvent, and catalysts on the incorporation of the benzyl group and the overall reaction efficiency was analyzed. The structures of the synthesized benzyl derivatives were elucidated using modern physicochemical techniques (IR, NMR). Based on the obtained results, optimal reaction conditions were proposed. Furthermore, the biological activity of the benzylated quinazolin-4-ones was preliminarily evaluated, and several promising candidates were identified. These findings broaden the prospects for developing quinazolin-4-one derivatives as novel biologically active compounds and provide a foundation for their application in pharmaceuticals and agrochemistry.

Keywords: *o*-Aminobenzoic acid, formamide, quinazoline-4-on, nitration, reduction, tin (II)-chloride dihydrate ($\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$), layered chromatography, IR, and NMR spectroscopy

Introduction

In recent years, various periparations based on many representatives of derivatives formed on the basis of heterocyclic compounds containing quinazoline have been introduced into agricultural and medical practice (Arun K. Ghosh., Margherita Bindisi. 2015). Currently, it is conducting

scientific and practical research aimed at determining the specific aspects of optimal synthesis, structure and reactivity of quinazolones and their new derivatives, as well as creating biologically active substances with new pharmacophore fragments in their composition (Singh K., Sharma P., Kumar A., Chaudhary A., Roy R., 2013). In medical

veterinary practice and agriculture, medicinal products created on the basis of heterocyclic compounds – quinazolones and sulfonamides, formed from condensation with benzene Ringas, are widely used. In particular, preparations created on the basis of compounds of this class are used as herbicides, fungicides (2–3-dimethylxinazolones), bactericides, antigelminths (quinazoline dressing), hypotensive (quinazoline brimacs) preparations (Singh K., Sharma P., Kumar A., Chaudhary A., Roy R., 2013). Quinazoline is widely used as an inhibitor of harmful substances involved in a large number of biochemical processes in the body. Therefore, scientific research is carried out to carry out the targeted synthesis and modification of new derivatives of these heterocyclic compounds, to determine their structure on the basis of modern methods, to check the various biological properties of the compounds obtained, to create new drugs based on selected biologically active substances (Alagar-samy V., Murugesan S., Dhanabal K., 2007).

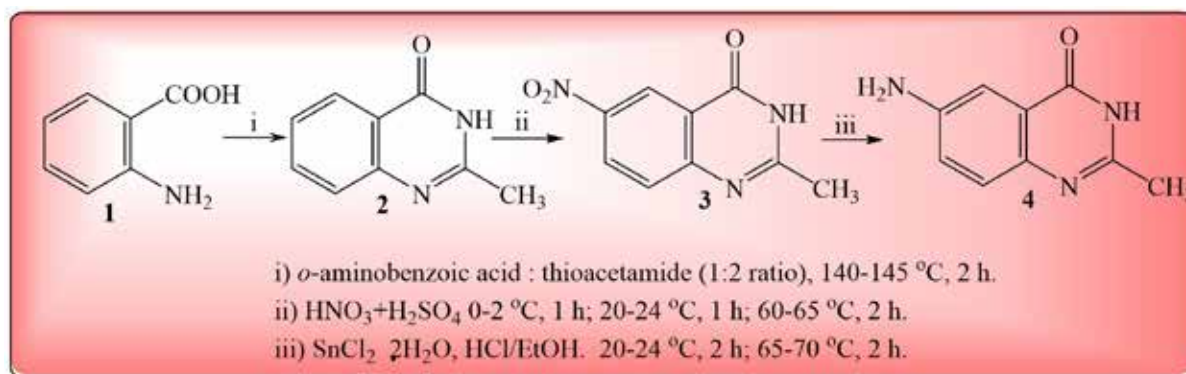
Derivatives based on quinazoline have been introduced into various periparatlarr agricultural and medical practices, created on the basis of a very large number of Representatives. Briquettes based on quinzoline have been widely used against viruses, microbes, fungi, colds and cancer (Arun K. Ghosh., Margherita Bindisi. 2015), as well as stimulants for plants (Singh K., Sharma P., Kumar A., Chaudhary A., Roy R.,

2013). Substances created on the basis of quinazoline are part of various preparations agricultural and medical practices, created on the basis of a very large number of representatives. Based on quinzoline have been widely used against viruses, microbes, fungicide, colds and cancer (Raffaella S., Daphne W., Daniel A., Jeffrey S., 2004), as well as stimulants for plants (Singh K., Sharma P., Kumar A., Chaudhary A., Roy R., 2013). In recent years, drugs such as imatinib, erlotinib, afatinib, which are used against tuberculosis and cancer patients, can be cited as examples. To this end, the synthesis, modification of various representatives of the biologically active – quinazoline ring in State 6, as well as the determination of their structure, gained relevance. Today, a lot of scientific work is being done on the synthesis and effective use of this type of substance (Wang S. B., Deng X. Q., Zheng Y., Yuan Y. P., Quan Z. S., Guan L. P., 2012).

Methods and results

Result and discussion. In the course of our research, an effective and convenient method of synthesizing 2-methylquinazolin-4-one (**2**) in the presence of o-aminobenzoic acid (**1**) and thioacetamide was implemented and obtained with a quantitative yield (95%). The resulting substance was nitrated under the action of a nitrating agent to synthesize 6-nitro-2-methylquinazolin-4-one (**3**) in 93% yield. The resulting 6-nitro-2-methylquinazolin-4-one was reacted with tin (II) chloride dihydrate ($\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$) and HCl to synthesize the corresponding 6-amino-2-methylquinazolin-4-one (**4**) (**Fig-1**) in 66% yield.

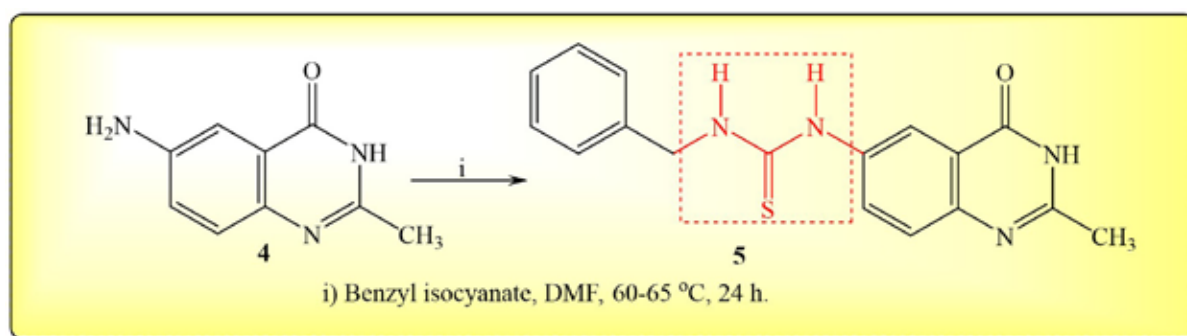
Figure 1.



The resulting substance (**4**) was thoroughly dissolved by placing 1 mmole in a 20 ml flask, connected to a magnetic mixer at 5 ml DMF, and 1.1 mmole allyl isothiocyanate was added on top. Connected to the refrigerator, the reaction was carried out and mixed in a magnet at 58–60 °C for 24 hours. The reaction was examined every 2 hours using thin-layer chromatography. Resulting substance (**4**) was thoroughly dissolved by placing 1 mmole in a 20 ml flask, connected to a magnetic mixer at 5 ml DMF, and 1.1 mmole benzyl isothiocyanate was added on top. Connected to the refrigerator, the

reaction was carried out and mixed in a magnet at 58–60 °C for 24 hours. The reaction was examined every 2 hours using thin-layer chromatography. When the starter substance was completely finished, it was rolled into the ice-cold water in the glass. The precipitate was filtrated and dried on 1-allyl-3-(4-oxo-3,4-dihydro-2-methylquinazolin-6-yl)thiourea (**5**) at filter paper. DMF: recrystallized in the water system (taken in a ratio of 1 to 1) and dried thoroughly. 1-benzyl-3-(2-methyl-4-oxo-3,4-dihydroquinazolin-6-yl)thiourea (**Fig-2**) was obtained with 86% (**5**).

Figure 2.



The liquefaction temperature of the resulting substance was determined by the values of 266–268°C and $R_f = 0.62$ (sistema; benzene acetone, 1:3 ratio), the structure of which was determined using the spectrum of modern physical research methods¹H NMR and ¹³C NMR (**Fig. 1, Fig. 2**).

¹H NMR spectrum of 2-methylquinazolin-4-one (400 MHz, CD₃OD, δ , ppm, J /Hz): 8.06 (1H, ddd, $J=7.9, 1.6, 0.6$, H-5), 7.65 (1H, m, H-7), 7.49 (1H, m, H-8), 7.34 (1H, m, H-6), 5.72 (1H, s, NH), 2.36 (3H, s, H-9).

¹³C NMR spectrum of 2-methylquinazolin-4-one (150 MHz, DMSO- d_6 +CCl₄, δ , ppm): 154.24 (C-2), 162.24 (C-4), 120.74 (C-4a), 126.24 (C-5), 124.80 (C-6), 133.10 (C-7), 125.52 (C-8), 149.12 (C-8a), 21.45 (C-9).

¹H NMR spectrum of 1-benzyl-3-(2-methyl-4-oxo-3,4-dihydroquinazolin-6-yl)thiourea (400 MHz, CD₃OD, δ , ppm, J /Hz): 8.32 (1H, s, H-2), 7.84 (1H, s, H5), 7.94 (1H, d, $J=8.3$, H7), 7.51 (1H, d, $J=8.7$, H8), 2.42 (1H, s, H-9), 7.73 (1H, s, H3), 12.01 (1H, s, H9), 9.63 (1H, s, H11) 4.14 (2H, s, H12), 5.89 (1H, s, H13),

5.21 (1H, dd, $J=17.2, 1.7$, H14a), 5.09 (1H, dd, $J=10.28, 1.55$, H14b).

¹³C NMR spectrum of 1-benzyl-3-(2-methyl-4-oxo-3,4-dihydroquinazolin-6-yl)thiourea (150 MHz, DMSO- d_6 +CCl₄, δ , ppm): 145.73 (C-2), 160.99 (C-4), 143.99 (C-4a), 134.96 (C-5), 129.97 (C-6), 123.34 (C-7), 127.54 (C-8), 21.4 (C-9), 118.61 (C-8a), 181.27(C-10), 46.62 (C-12), 138.59 (C-13), 116.25 (C14).

Conclusion

Quinazoline-4-on (**2**), which has a gercyclic structure, was obtained in absolute units in the simplest and most convenient way. After nitrolizing the resulting substance (**3**), a recurrence reaction was carried out. As a result of the reaction of the resulting substance (**4**) with isothiocyanate, the (**5**) compounds stored in the thiomochovina fragment were synthesized in high flour.

Acknowledgments. This work was supported by: Akad. S. Yu. Yunusov Institute of the Chemistry of Plant Substances, Academy of Sciences of the Republic of Uzbekistan. department of Organic synthesis.

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submitted 19.05.2026;

accepted for publication 03.06.2026;

published 30.06.2026

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Section 2. Computer sciences

DOI:10.29013/AJT-26-5.6-63-70



ARCHITECTURE OF DIGITAL PLATFORMS IN HIGH-LOAD ENVIRONMENTS: APPROACHES TO MODULARITY, SCALING, AND INTEGRATION WITH EXTERNAL SERVICES

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Cite: Berezhnoy A. (2026). *Architecture of digital platforms in high-load environments: approaches to modularity, scaling, and integration with external services*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-63-70>

Abstract

The article examines architectural approaches to the design of digital platforms in high-load environments, with a particular focus on modularity, scaling, and integration with external services. It is shown that the resilience of platform solutions is determined by the consistency of architectural decomposition, load management mechanisms, and the integration layer. The study analyzes the features of monolithic, modular, and microservices-based system organization, as well as architectural mechanisms that ensure fault tolerance, load controllability, and predictability of intersystem interaction. It is substantiated that an effective architecture should provide failure isolation, adaptive resource distribution, and controlled operation with external dependencies. The conclusion is made that the design of high-load digital platforms requires a systemic architectural approach.

Keywords: *digital platforms, high-load systems, modular architecture, scaling, API integration, fault tolerance, platform architecture*

Introduction

The expansion of the digital economy, platform-based business models, and distributed information systems has increased the demands placed on the architecture of digital platforms operating under high and uneven load. Contemporary platform solutions must not only process large volumes of user requests, transactions, and data flows, but also remain stable under intensive interaction with external services, API interfaces,

and distributed data sources. Under such conditions, architectural design acquires strategic importance, since platform scalability, adaptability to changing operating conditions, manageability of integration layers, and the possibility of further system evolution without critical growth in complexity depend on it.

Scholarly interest in this issue is associated with the need to systematize approaches to the design of high-load digital platforms in

which modularity, scalability, and integration compatibility function as interrelated characteristics of a unified architectural model. Particular importance lies in examining the principles and architectural patterns that make it possible to combine performance, fault tolerance, and platform flexibility amid continuous functional expansion and increasingly complex external interactions. The purpose of the article is to analyze architectural approaches to the design of digital platforms in high-load environments, with emphasis on modularity, scaling mechanisms, and integration with external services.

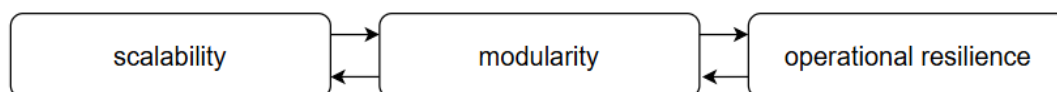
Theoretical foundations of designing digital platforms in high-load environments

A modern digital platform in a high-load environment should be understood not simply as a set of application services, but as

a multilayer architectural system that must simultaneously support intensive request processing, resilience to uneven workloads, controllable change management, and integration compatibility with external services (Chen X., 2025). The relevance of this approach is confirmed by current infrastructure trends: according to CNCF, cloud-native technologies have reached 89% adoption among surveyed organizations, 80% run Kubernetes in production, 60% use CI/CD for most or all applications, and 77% apply GitOps principles in deployment (CNCF, 2025). These figures indicate that high-load operation is no longer an exceptional case, but a standard condition for a substantial share of digital platforms.

From a theoretical perspective, a high-load digital platform should be examined through the prism of three interrelated characteristics (fig. 1).

Figure 1. *Interrelated characteristics of a high-load digital platform*

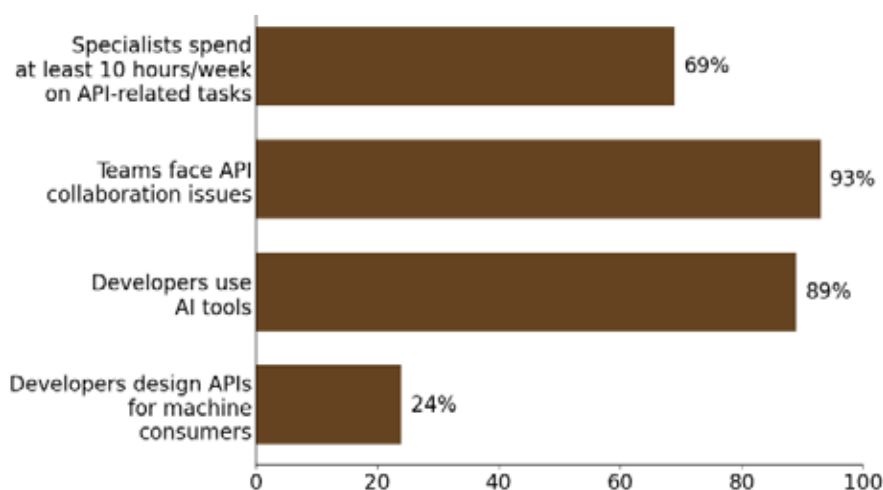


Scalability reflects the ability of a system to maintain acceptable response times and throughput as the number of users, transactions, and integration calls increases. **Modularity** ensures a clear distribution of responsibilities across components and supports the localization of changes, which is especially important under conditions of continuous functional expansion. **Operational resilience** describes the ability of a platform

to preserve a working state in the presence of failures, overloads, and degradation of external dependencies.

Of particular importance for platform architecture theory is the **growing role of APIs** as the primary mechanism of inter-system interaction. According to the Postman 2025 report, 69% of specialists spend at least 10 hours per week on API-related tasks (fig. 2).

Figure 2. *Selected indicators characterizing the growing architectural role of APIs in digital platforms according to the Postman 2025 report (Postman, 2025)*



These indicators are theoretically significant because they reflect a transition from a model in which APIs served as auxiliary integration mechanisms to one in which APIs become the architectural core of the platform and, at the same time, a source of new requirements for contracts, error typing, access control, and the predictability of interface behavior.

High-load environments increase platform **dependence on the quality of the integration layer** and make the reliability of external calls critically important. As reported in the Uptrends 2025 study, the availability of APIs on average decreased to 99.46% for Q1 2025 from 99.66% in Q1 2024, and at least 67% of all the incidents associated with monitoring were due to API problems, but not TLS or timeouts. From an architectural perspective, this implies that external integration is not a secondary task anymore – every external component represents one more risk area, and therefore, there should be mechanisms for failures isolation and degradation.

Finally, a fundamental feature of high-load platforms is their **dependence on a cloud-native and distributed logic** of system organization. In these settings, the quality of architecture does not depend on the performance of the core of one particular application but rather on the synergy of decomposed services, elastic resource allocation, and robust integration facilities. Therefore, we can state that the theoretical basis for high-performance platform development

consists in the combination of scalability, modularity, and reliability in a consistent distributed architecture.

Thus, the theoretical understanding of digital platforms in high-load environments extends beyond infrastructure capacity alone. It requires a systemic architectural perspective in which performance, adaptability, and integration stability are treated as interdependent properties of a single platform model.

Architectural approaches to modularity and scaling of platform solutions

The development of a high-load digital platform requires the selection of an architectural model that can simultaneously support functional evolution, localization of changes, and controlled scaling of individual components. In applied engineering practice, the primary comparison is usually made between monolithic architecture, modular monolith, and the microservices model (table 1).

At the same time, contemporary literature and engineering recommendations agree that the transition to a more complex architecture is not justified in itself, but only in the presence of clear indicators, such as an increase in the number of teams, uneven workload distribution across functional areas, difficulties associated with a unified release cycle, and the need for isolated scaling of individual domains (Shah A., 2025).

Table 1. *Comparative characteristics of architectural approaches to modularity and scaling of platform solutions*

Architectural approach	Key characteristics	Advantages in high-load environments	Limitations and risks
Monolithic architecture	A single application with a shared codebase, common deployment contour, and centralized management.	Simplicity of development and maintenance at the initial stage, low overhead of internal interactions, unified testing contour.	Limited scaling flexibility, high coupling of components, risk of system-wide degradation when individual functions are overloaded.
Modular monolith	A single application divided into functionally isolated modules with defined internal responsibility boundaries.	Higher change manageability, reduced internal coupling, possibility of gradual architectural evolution.	Retention of a shared deployment contour, dependence of modules on common infrastructure, limited isolated scaling.

Architectural approach	Key characteristics	Advantages in high-load environments	Limitations and risks
Microservices architecture	A set of autonomous services with independent deployment and interaction through APIs or event-driven mechanisms.	Independent scaling of components, technological flexibility, failure isolation, support for distributed development.	High operational complexity, increased requirements for monitoring, orchestration, contracts, and management of distributed interactions.

From a theoretical perspective, modularity has value only when it is supported by actual isolation of data and component responsibilities; in high-load environments, it should therefore be understood not merely as code structuring, but as an organizational principle based on domain separation, minimized cross-dependencies, API contracts, and service-level scaling boundaries.

A quantitative illustration of the effect of architectural transformation on scaling performance is provided by the **VTEX case** pub-

lished by AWS in 2025. During the modernization of part of its platform infrastructure, the company migrated legacy components to Amazon EKS, allowing it to assess how architectural reorganization affects scaling speed and latency. The shift to a more modular and orchestrated environment significantly reduced scale-up time while preserving comparable latency, which makes this case methodologically relevant for evaluating the effectiveness of architectural restructuring in platform solutions (table 2).

Table 2. *Changes in scaling and latency indicators after the migration of VTEX components to Amazon EKS (AWS, 2025)*

Indicator	Before architectural transformation	After migration to Amazon EKS	Change
Average scale-up time until pod startup	about 7 min	73 s	88% reduction
p50 latency	about 19 ms	about 20 ms	no significant change
p90 latency	about 155 ms	about 162 ms	slight increase
p95 latency	about 324 ms	about 326 ms	virtually unchanged

These results show that scaling efficiency depends not only on available computing resources, but also on the platform's architectural readiness for containerization, orchestration, and automatic workload redistribution. In practical terms, this confirms that a more modular architecture can significantly improve the system's response to growing load without noticeably degrading user-critical performance indicators.

A clear illustration of architectural maturity under extreme load is provided by **Shopify's BFCM readiness case**. Its methodological value lies in the fact that platform resilience is evaluated not only through actual peak-period operation, but also through systematic large-scale stress testing aimed at verifying scalability limits and identifying potential bottlenecks in advance (table 3).

Table 3. *Selected indicators of Shopify's load readiness in preparation for BFCM (Shopify, 2025)*

Indicator	Value	Architectural relevance
Simulated load in fire drills	150% of the previous peak	Verification of platform resilience beyond historical peak levels.

Indicator	Value	Architectural relevance
Edge requests in 2024	1.19 trillion	Reflect the scale of external traffic handled by the platform.
Database requests in 2024	10.5 trillion	Indicate the intensity of the internal data-processing layer.
Peak edge traffic	284 million requests/min	Demonstrates the maximum load on external entry points.
Checkout load in the fourth scale test	over 80,000/min	Shows the stability of a critical user path under extreme load.

These data indicate that the resilience of a high-load platform depends not only on the chosen architectural model, but also on continuous validation of its behavior under stress conditions. This dependence is also shaped by low-level infrastructural factors, as seen, for example, in Linux-based high-load environments, where memory management efficiency directly affects latency stability, resource saturation, and the platform's ability to sustain peak load without cascading degradation (Otkidach I., 2026). In practical terms, this means that modularity and scalability must be supported by regular load testing capable of revealing hidden constraints in queues, memory, routing, and service interactions.

Taken together, these observations show that approaches to modularity and scaling should be assessed not as abstract design preferences, but as practical mechanisms for controlling growth, isolating failures, and adapting to uneven demand. Architectural maturity is therefore determined not only by the select-

ed design pattern, but also by the platform's readiness for orchestration, controlled scaling, and continuous load validation.

Integration of digital platforms with external services and data sources

In high-load environments, interaction with external services should be treated as a distinct architectural layer rather than as an auxiliary technical function (Egbert S. & Ulbricht L., 2024). From a theoretical standpoint, this layer performs several critical tasks, including data format alignment, management of differences in external SLA conditions, limitation of cascading failures, and preservation of predictable platform behavior under unstable API conditions. In contemporary architecture practice, these objectives are addressed through synchronous and asynchronous interaction models, and the choice between them is determined not by implementation convenience, but by the characteristics of the business operation (table 4).

Table 4. *Comparative characteristics of synchronous and asynchronous interaction models in platform integration*

Interaction model	Key characteristics	Advantages	Limitations
Synchro-nous	Immediate request-response interaction with direct dependency on the availability and response time of the external service.	Simplicity of control flow, immediate result delivery, convenient for operations requiring instant confirmation.	Higher sensitivity to latency, timeouts, and external service failures; limited resilience under peak load.
Asynchro-nous	Request acceptance with deferred processing through queues, brokers, or event-driven mechanisms.	Better decoupling of components, higher resilience to load spikes, improved fault isolation, support for load leveling.	Increased implementation complexity, delayed result delivery, additional requirements for monitoring, idempotency, and message handling.

For example, in B2B platform environments, the integration layer often includes not only data exchange interfaces, but also external identification mechanisms that influence access control, transaction reliability, and the structure of interorganizational service interaction (Miloserdov A., 2026). Under such conditions, integration architecture must account for the fact that digital identification services become part of the operational logic of the platform rather than a purely auxiliary security component.

From a technical perspective, the main integration problem is that external systems rarely share the same load profile as the platform itself. This makes an intermediate integration layer necessary for normalization, routing, rate limiting, buffering, and redelivery. Therefore, integration with external services should rely not only on an API gateway, but also on queues, backpressure controls, and idempotent message handling.

An equally important aspect is the **fault tolerance of the integration layer**. Uncontrolled retries in a distributed environment can trigger a retry storm, amplifying the degradation of an external service instead of resolving it. Microsoft's 2025 Azure Architecture Center guidance emphasizes that a mature integration architecture should rely on bounded retries, circuit breakers, bulkhead segmentation, and asynchronous offloading rather than on any single recovery mechanism.

Observability is an essential element of integration architecture (Sakinala K., 2025). In distributed platforms, failures of external services usually appear not as isolated incidents, but as higher latency, queue buildup, timeout growth, or downstream degradation.

Google Cloud's reliability guidance highlights tracing and buffering mechanisms for reliable asynchronous delivery and controlled retry. Therefore, full integration with external data sources requires end-to-end tracing, correlation IDs, lag metrics, quota monitoring, and logging of adapter-level transformations; otherwise, even a formally correct integration remains operationally opaque under high load.

The integration with other services in a high-load application should be regarded as an architectural aspect rather than just a technical means of establishing connectivity. The efficiency of such integration relies on the proper interplay of the following aspects: interaction model, load control, fault isolation techniques, and observability measures. As a result, architecture sophistication in platform integration involves not only connectivity issues but also stability and controllability in the presence of load imbalance and dependency problems.

Architectural patterns and practical recommendations for ensuring the resilience of digital platforms

At the operational stage of a high-load digital platform, resilience depends not only on overall architectural design, but also on applied patterns that limit failure propagation, stabilize behavior under load spikes, and support predictable recovery. Azure guidance emphasizes that, in distributed systems, such patterns should serve as core architectural building blocks. Among the most relevant for high-load platforms are Bulkhead, Cache-Aside, Asynchronous Request-Reply, and Anti-Corruption Layer (Ataei P. & Staegemann D., 2023). The key patterns are summarized in table 5.

Table 5. *Key architectural patterns for ensuring the resilience of digital platforms in high-load environments*

Architectural pattern	Primary function	Benefit in high-load environments	Main limitation
Bulkhead	Isolation of components into separate resource pools.	Prevents cascading failure propagation across services and load domains.	Requires careful allocation of resource limits and capacities.

Architectural pattern	Primary function	Benefit in high-load environments	Main limitation
Retry with Backoff	Repetition of temporarily failed calls.	Increases the probability of successful response during short-term network or service failures.	May intensify degradation if configured improperly.
Circuit Breaker	Temporary blocking of calls to a degraded service.	Reduces pressure on an unavailable dependency and accelerates overall recovery.	Requires accurate threshold settings and half-open policies.
Queue-Based Load Leveling	Decoupling request intake from processing through a queue.	Smooths peak load and reduces the need for excessive overprovisioning.	Introduces asynchrony and may increase end-to-end latency.
Cache-Aside	Offloading a portion of read operations to cache.	Reduces pressure on the primary data store and improves response time in typical access scenarios.	Requires effective cache invalidation and consistency control.
Anti-Corruption Layer	Adaptation of an external or legacy data model.	Localizes integration complexity and protects the internal domain model from external inconsistencies.	Adds transformation overhead and adapter maintenance effort.

The systemic importance of these patterns is confirmed by official reliability guidance. Azure emphasizes that the Bulkhead pattern isolates components and prevents cascading failures, while asynchronous queue-based communication helps preserve platform operation when a downstream component fails. Queue-Based Load Leveling also separates request intake from processing speed, absorbs sudden demand spikes, and reduces the need for overprovisioning. Thus, resilience in a high-load platform should be built not around a single “reliable” service, but around controlled isolation of load and failures across multiple processing paths.

Particular attention should be paid to the **proper configuration of retry logic**. In its current description of the retry storm antipattern, Microsoft shows that uncontrolled request retries can themselves become a source of overload: instead of recovering after a failure, the system receives new waves of requests precisely during the period of degradation.

Finally, resilience depends **not only on the use of architectural patterns, but also on validation** of their actual behavior in operation. The State of Observability 2025

report shows that only 15.2% of organizations have reached a mature observability stage, while about half remain at an early stage. This indicates that even well-chosen patterns do not ensure resilience on their own unless the platform is supported by a mature observability layer capable of detecting queue buildup, resource saturation, dependency failures, and latency degradation. Thus, practical platform resilience emerges from the combination of architectural patterns, load constraints, and operational observability rather than from any single technology.

Overall, the analysis shows that the resilience of a high-load digital platform depends not on individual patterns taken separately, but on their coordinated use within a controlled operational environment. Architectural maturity, therefore, is expressed in the ability to combine failure isolation, adaptive load handling, and observability into a unified mechanism of stable platform operation.

Conclusion

The architecture of digital platforms in high-load environments is formed as a system of interrelated decisions in which modulari-

ty, scaling, and integration resilience cannot be considered separately. The effectiveness of a platform depends not only on computing resources or the chosen technology stack, but primarily on the quality of architectural decomposition, the ability to localize changes, redistribute load across components, and maintain stable operation as external interactions become more complex. Under such conditions, resilience is achieved through targeted scaling, clear separation of responsibilities, isolating architectural patterns, and a controllable integration layer.

The design practice of high-load platforms shows that long-term reliability and

adaptability are ensured not by a single architectural solution, but by a coordinated set of principles covering internal service organization, peak-load handling, and interaction with external data sources. As digital ecosystems expand, observability, fault tolerance, API predictability, and the ability to evolve architecture without critical growth in complexity become increasingly important. For this reason, the development of digital platforms requires a shift from local optimization of individual components to a systemic architectural approach focused on scalability, structural flexibility, and stable operation under high load.

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submitted 18.05.2026;

accepted for publication 02.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-71-76



SECURITY AS A FEATURE: THE NEXT COMPETITIVE ADVANTAGE IN SOFTWARE PRODUCTS

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Cite: Polezhaev A. (2026). *Security as a Feature: The Next Competitive Advantage in Software Products*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-71-76>

Abstract

Contemporary software products face a structural authentication vulnerability that perimeter-based and point-of-entry credential systems cannot resolve: once a session is established, the identity of the operating party is never re-verified. This paper examines the theoretical and empirical basis of that vulnerability, reviews the inadequacy of extant single-modality behavioral biometric approaches, and contextualizes a continuous, passive, multi-modal behavioral authentication framework as a scientifically grounded response. Drawing on cognitive neuroscience, human-computer interaction theory, and machine learning literature, the paper establishes that behavioral individuality in keyboard and pointer interaction is not a statistical artifact but a direct physiological signal exploitable for continuous identity verification. The proposed framework integrates five behavioral signal channels (keystroke dynamics, mouse trajectory, pointer dwell, scroll rhythm, and application transition timing) into a two-tier stacked ensemble classifier with session-level temporal encoding, per-user threshold calibration, and adversarially robust adaptive profile maintenance. Empirical evaluation across 64 users yielded a False Acceptance Rate of 0.28%, a False Rejection Rate of 1.76%, and a mean identity substitution detection latency of 31 seconds, representing statistically significant improvements over all single-modality baselines. The article situates these results within the broader argument that security, when implemented as an architecturally integrated ambient property, constitutes a genuine source of product differentiation and competitive advantage.

Keywords: *continuous authentication; behavioral biometrics; keystroke dynamics; session integrity; machine learning; insider threat; software security; multi-modal fusion; competitive advantage*

Introduction

The commercial software industry has historically treated security as a compliance obligation rather than a product attribute. Authentication systems built around discrete

credential verification events (passwords, hardware tokens, one-time codes) provide no mechanism for monitoring the session once access has been granted, leaving the post-authentication period without any form

of identity continuity verification (Bonneau et al., 2012). This design reflects an implicit but consequential assumption: that the identity of the session initiator remains stable throughout the session. The accumulated body of security incident data collected over two decades contradicts that assumption with sufficient consistency to warrant its rejection as an architectural premise.

Behavioral biometrics research provides a theoretically grounded response to this vulnerability. The observation that individuals exhibit stable, measurable, and individually distinctive patterns in their interaction with computing input devices has been documented since at least the 1980s, spanning keystroke dynamics, mouse movement, touch gestures, and gait analysis (Rybnik et al., 2008; Stylios et al., 2022). The core theoretical premise, that motor execution patterns reflect neurologically and physiologically individualized characteristics stable within subjects and discriminative between subjects, is supported by neuroimaging and motor learning research demonstrating that extensively practiced movement sequences consolidate into individual-specific low-level control circuits whose output characteristics are both stable and person-distinctive (Dhawale et al., 2022).

The persistence of this deployment gap is attributable to three distinct limitations of prior systems. Published single-modality systems exhibit Equal Error Rates that remain too high for operational reliance, with keystroke-only implementations typically yielding EERs of 3 to 7% (Morales et al., 2016; Rybnik et al., 2008). Reliance on population-level fixed thresholds, which fail to account for substantial inter-individual variance in behavioral baselines, produces false rejection rates sufficient to generate organizational resistance to adoption (Stylios et al., 2022). The absence of adaptive profile maintenance further prevents such systems from accommodating natural behavioral drift, specifically the gradual change in typing and pointing characteristics that individuals exhibit over extended periods, resulting in progressive false rejection inflation over the deployment lifetime (Bailey et al., 2014). This paper argues that each of these limitations is addressable through an integrated

architectural design, and that the resulting system constitutes not merely a technical improvement but a strategic asset for software products that incorporate it. The subsequent sections present the theoretical foundations of the problem, describe the proposed framework, report experimental results, and discuss implications for software product design and competitive differentiation.

Materials and Methods

The discriminative validity of behavioral biometric signals rests on a well-established physiological basis: inter-individual variation in input interaction patterns is a necessary consequence of how motor skills are acquired and consolidated. This is most clearly demonstrated in the neuroscience of motor sequence learning as it applies to typewriting. Research on the neural circuits underlying extensively practiced motor sequences has shown that repeated execution consolidates movement programs into low-level cortical and subcortical control circuits, including the primary motor cortex and the sensorimotor striatum, producing execution patterns that are faster, smoother, and less cognitively demanding than novel movements (Dhawale et al., 2022). Because each individual's keyboard history is unique in volume, style, and temporal distribution, the resulting low-level circuits differ across individuals in ways that are directly observable as inter-individual differences in keystroke timing distributions.

The proposed framework operates as a background software process requiring no dedicated biometric hardware; commodity input peripherals (keyboard and mouse) constitute the sole sensing apparatus. Six co-operating modules form the system: a Signal Acquisition Layer (SAL), a Feature Extraction Engine (FEE), an Ensemble Classifier (EC), an Adaptive Profile Store (APS), a Confidence Scoring Module (CSM), and a Session Integrity Manager (SIM). The SAL captures five concurrent behavioral signal channels: keystroke timing metadata at microsecond resolution without recording key identifiers, mouse pointer trajectory at a minimum of 100 Hz, pointer dwell and click dynamics, scroll event sequences, and application focus transition timing. Raw event buffers are retained exclusively in volatile memory

with a 60-second rolling retention window; no behavioral event sequences are written to persistent storage, satisfying the data minimization principles of contemporary privacy regulation.

At five-second intervals, the FEE extracts a 114-dimensional feature vector from a 30-second sliding window across all five channels, applying quality screening to reject windows with insufficient data density. Per-feature z-score normalization using the enrolled user's own behavioral statistics ensures that the classifier operates on deviation scores expressed in units of the individual's behavioral standard deviation; this per-user normalization scheme renders threshold values interpretable as multiples of the individual's enrollment distribution spread, in contrast to population-calibrated approaches where threshold values carry no user-specific meaning.

The Ensemble Classifier implements a two-tier stacking architecture. The base classifier layer comprises five modality-specific one-class Support Vector Machines trained on each enrolled user's per-modality sub-vectors, and five modality-specific Long Short-Term Memory networks that encode 60 seconds of temporal behavioral context. The session-level temporal encoding provided by the LSTM components addresses a critical limitation of window-level statistical classifiers: replay attacks and session impersonation attempts do not reproduce the characteristic temporal evolution exhibited by genuine users, including the motor warm-up trajectory at session start and fatigue-related drift during extended sessions (Abuhamad et al., 2020). A gradient-boosted meta-classifier trained on 50,000 population-level base-classifier output vectors, including 5,000 adversarially generated mimicry samples, combines the ten base-classifier outputs into a single Platt-scaled probabilistic confidence score.

Per-user threshold calibration replaces the population-level fixed thresholds characteristic of prior systems (Bailey et al., 2014; Morales et al., 2016). The upper threshold T_{upper} is set at the 5th percentile of the enrolled user's own in-enrollment composite score distribution, ensuring that at most 5% of authentic sessions fall below the threshold

under enrollment-equivalent conditions. The lower threshold T_{lower} is set at $0.60 \times T_{upper}$, defining a graduated response zone between heightened monitoring and explicit challenge.

The Session Integrity Manager implements a four-state finite automaton with states designated as Active, Watchful, Challenged, and Suspended, each carrying differentiated enforcement actions. The Watchful state increases monitoring resolution without any user-visible action. The Challenged state presents a brief typed text passage for keystroke-based re-verification. The Suspended state blocks session interactions and writes a structured security event to the system log. A configurable Privilege Reduction Mode substitutes graduated access restriction for full suspension in environments where complete session termination would cause service disruption.

Adaptive profile maintenance applies a Mahalanobis-distance-bounded weighted exponential moving average with a learning rate of 0.05 to update the enrolled behavioral model from fully authenticated sessions. A rolling 10-session drift velocity monitor detects adversarial profile poisoning attempts and triggers automatic model reversion upon threshold exceedance.

Performance evaluation was conducted across 64 users, each contributing 15 authenticated sessions and 5 impostor sessions of 60 minutes duration. Single-modality baselines were evaluated using identical classifier architecture and protocol, with four of the five modalities disabled in each baseline condition. The LSTM pre-training population comprised 320 users across 30 sessions each. The meta-classifier training set included 5,000 adversarially generated impostor samples from trained human mimics who had observed target users' behavioral patterns, ensuring that mimicry resistance was tested under adversarially realistic.

Results

The multi-modal framework achieved a False Acceptance Rate (FAR) of 0.28%, a False Rejection Rate (FRR) of 1.76%, an Equal Error Rate (EER) of 1.02%, and a mean identity substitution detection latency of 31.4 seconds. The reduction in EER from

the keystroke-only baseline (3.50%) to the multi-modal framework (1.02%) amounts to a 70.9% improvement relative to the single-modality baseline value, indicating that the addition of four behavioral channels yields error reduction disproportionate to the number of added modalities. The mimicry attack FAR reduction is more pronounced: from 11.2% for the keystroke-only condition to 0.003% for the full framework. This outcome is consistent with the theoretical prediction derived from the independence of the five behavioral channels: if per-modality mimicry success probability is approximately 0.12 for trained human mimics with prior observation access, the joint probability of satisfying all five SVM acceptance criteria simultaneously is approximately 2.5×10^{-5} . The near-correspondence between this theoretical estimate and the empirically observed rate indicates that the five modalities function as substantially independent discriminative dimensions, producing security gains that exceed those achievable through linear combination.

Detection latency improved from 48.3 seconds for the keystroke-only baseline to 31.4 seconds for the full framework, a reduction of approximately 35%. The session suspension false positive rate of 1.6% represents a substantial improvement over the 4.1% rate of the keystroke-only baseline. At 60-minute session granularity, a false positive rate of 1.6% implies that a user conducting four working sessions per day would experience an incorrect suspension event less than once per week on average, a frequency within operationally acceptable bounds for high-security enterprise environments.

Discussion

The empirical results indicate that the proposed framework substantially reduces the authentication gap that point-of-entry credential systems leave open. Session hijacking bypasses Multi-Factor Authentication entirely because the MFA credential is consumed at session initiation and the active session token carries no intrinsic identity binding (Anderson, 2020; Alzahrani et al., 2022). A mean detection latency of 31.4 seconds limits the window during which an identity substitution event can persist un-

detected, reducing the practical feasibility of data exfiltration within a single hijacked session in typical organizational computing environments.

A productive distinction exists between security as a compliance artifact and security as an ambient product attribute. Compliance-oriented security imposes costs on both vendor and user without producing measurable positive value for either party. Ambient security integrates protective mechanisms that operate without user awareness or active engagement under ordinary conditions (Bonneau et al., 2012). Behavioral authentication, as implemented in the proposed framework, instantiates this category: the system operates within the background of normal computing activity and initiates security events only when behavioral evidence crosses quantitatively calibrated thresholds (Stylios et al., 2022).

The competitive value of this architecture lies in the product's capacity to provide demonstrably stronger post-authentication security guarantees while simultaneously delivering a less obstructive user experience than token-based or challenge-based continuous authentication alternatives (Alzahrani et al., 2022). In market segments where security posture functions as a purchasing criterion, including financial services, healthcare, legal technology, government software, and enterprise productivity tools, the availability of verifiable continuous authentication metrics represents a quantifiable differentiator that can be communicated directly to procurement decision-makers and auditors (Anderson, 2020).

Conclusion

The authentication vulnerability inherent in point-of-entry credential verification is structural in nature: stronger passwords, additional login factors, and more sophisticated session token mechanisms do not address the post-authentication period to the degree required to counter identity substitution, session hijacking, and insider threat activity. The theoretical and empirical literature reviewed in this paper converges on behavioral biometrics as the only passive, hardware-free mechanism available for continuous post-authentication identity verification, grounded

in physiological and cognitive foundations that make behavioral individuality in keyboard and pointer interaction both discriminatively valid and persistently stable over time.

The multi-modal stacked ensemble framework developed by the author addresses the limitations of prior systems through specific architectural decisions with documented empirical effects, yielding a 1.02% Equal Error Rate, a 0.003% mimicry attack FAR, and a 31.4-second mean detection la-

tency. These results demonstrate that the engineering requirements of operational continuous behavioral authentication can be met within the resource envelope of standard enterprise computing hardware. For software products operating in security-sensitive market segments, integration of this capability represents both a measurable advancement in the protective function delivered to users and a sustainable competitive differentiator verifiable through auditable performance metrics.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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Section 3. Medical science

DOI:10.29013/AJT-26-5.6-77-82



THYROID DYSFUNCTION IN PATIENTS RECEIVING COMBINED TREATMENT FOR BREAST CANCER: A PROSPECTIVE CLINICAL STUDY

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Cite: Azimova M. A., Nasirova Kh. K., Kurbanov D. B. (2026). *Thyroid Dysfunction in Patients Receiving Combined Treatment for Breast Cancer: A Prospective Clinical Study*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-77-82>

Abstract

Breast cancer is the most common malignancy among women worldwide and remains a leading cause of cancer-related mortality. Combined treatment approaches significantly improve survival but are associated with systemic complications, including endocrine toxicity. The thyroid gland is particularly sensitive to anticancer therapies.

This prospective study aimed to evaluate functional and structural changes of the thyroid gland in patients with breast cancer during combined treatment. A total of 136 patients with stage II–III breast cancer and 23 control patients with stage I disease were included. Thyroid function was assessed by measuring serum levels of TSH, free T4 (fT4), free T3 (fT3), and anti-thyroid peroxidase antibodies (anti-TPO), while ultrasound was used to evaluate structural changes.

The results demonstrated a significant increase in TSH levels and a decrease in fT4 and fT3 concentrations in patients receiving combined therapy compared to controls ($p < 0.0001$). The prevalence of hypothyroidism exceeded 60%, with more pronounced changes observed in patients receiving neoadjuvant therapy. Ultrasound examination revealed structural abnormalities in approximately 40% of patients. Clinical symptoms consistent with hypothyroidism were also significantly more frequent in the treatment groups.

In conclusion, thyroid dysfunction is a common manifestation of endocrine toxicity in patients undergoing combined treatment for breast cancer. Routine monitoring of thyroid function and ultrasound evaluation are recommended for early detection and management of these disorders.

Keywords: *breast cancer; thyroid dysfunction; hypothyroidism; chemotherapy; endocrine toxicity; neoadjuvant therapy; thyroid ultrasound; TSH; fT4; fT3; autoimmune thyroiditis*

Introduction

Breast cancer ranks first in the structure of oncological morbidity among women worldwide and remains a leading cause of cancer-related mortality (Jemal, A., Bray, F., Center, M.M., Ferlay, J., Ward, E., & Forman, D., 2011; Bray, F., Ferlay, J., Soerjomataram, I., Siegel, R.L., Torre, L.A., & Jemal, A., 2018). According to international registries, more than 2.3 million new cases are registered annually, and the increasing trend persists (Jemal, A., Bray, F., Center, M.M., Ferlay, J., Ward, E., & Forman, D., 2011). In Central Asian countries, including the Republic of Uzbekistan, a steady rise in incidence rates and a shift toward younger patient populations are observed (Early Breast Cancer Trialists' Collaborative Group, 2012).

Modern advances in molecular diagnostics, targeted and hormonal therapy have significantly improved overall and disease-free survival (Harbeck, N., Penault-Llorca, F., Cortes, J., et al. 2019; National Comprehensive Cancer Network (NCCN). 2024). Combined treatment regimens, including surgery, neoadjuvant and adjuvant chemotherapy, radiotherapy, and endocrine therapy, represent the standard management for patients with stage II–III disease (ESMO Guidelines Committee. 2021; Curigliano, G., Cardinale, D., Suter, T., et al. 2012). At the same time, intensification of therapy is accompanied by an increase in systemic complications, which requires expansion of monitoring for associated disorders (Torino, F., Corsello, S.M., & Salvatori, R., 2012).

In recent years, increasing attention has been paid to the problem of endocrine toxicity of anticancer treatment (Faje, A.T., 2016; Illouz, F., Laboureau-Soares, S., Dubois, S., et al., 2014). The thyroid gland is among the target organs sensitive to cytotoxic drugs, targeted agents, and immunomodulatory therapy (Iyer, P.C., Cabanillas, M.E., Waguespack, S.G., et al., 2018). Mechanisms of damage include direct cytotoxic injury to thyrocytes, impairment of peripheral conversion of thyroid hormones, vascular changes, and immune reactions (Brent, G.A., 2012).

Thyroid hormones play a fundamental role in the regulation of energy metabolism, cell proliferation, differentiation, and apoptosis (Biondi, B., & Cooper, D.S., 2008). Dis-

turbances in their secretion may lead to decreased treatment tolerance, reduced quality of life, and the development of asthenic syndrome, which is often mistakenly interpreted as chemotherapy toxicity (Abdel-Rahman, O., ElHalawani, H., & Fouad, M., 2015).

According to various authors, the incidence of subclinical and overt hypothyroidism in oncology patients ranges from 30% to 60%, depending on treatment regimens (Faje, A.T., 2016; Mannavola, D., Coco, P., Vannucchi, G., et al., 2007; de Filette, J., Andreescu, C.E., Cools, F., et al., 2019). A particularly high risk of thyroid dysfunction has been described with the use of targeted agents and combined treatment regimens (Brent, G.A., 2012; Ditsch, N., Liebhardt, S., von Koch, F., et al., 2010). However, data on thyroid status in patients with breast cancer undergoing neoadjuvant and adjuvant chemotherapy remain limited and contradictory (Hegedüs, L., 2004).

In addition to functional changes, structural abnormalities of the thyroid gland detected by ultrasound are also important, including decreased echogenicity, parenchymal heterogeneity, and signs of autoimmune inflammation (Vanderpump, M.P.J., 2011). A comprehensive assessment of hormonal and ultrasound parameters allows for a more accurate determination of the nature and severity of the lesion.

Thus, the study of functional and structural status of the thyroid gland in patients with breast cancer receiving combined treatment represents a relevant scientific and clinical task.

Objective

To evaluate functional and structural changes of the thyroid gland in patients with breast cancer during combined treatment.

Materials and Methods

The study was conducted in a prospective format at a specialized oncology center from November 2023 to January 2025.

The study included 136 patients aged 38 to 68 years (mean age 52.4 ± 6.8 years) with morphologically confirmed stage II–III breast cancer.

The control group consisted of 23 patients (mean age 50.9 ± 5.7 years) with stage

I disease who did not receive aggressive combined therapy.

Patients of the main cohort were divided into two groups:

First group (n=62) – surgical treatment followed by adjuvant chemotherapy.

Second group (n=74) – neoadjuvant chemotherapy followed by surgery and adjuvant therapy.

Inclusion criteria:

1. Age over 18 years
2. Histologically confirmed diagnosis
3. Absence of previously diagnosed thyroid diseases
4. Written informed consent

Exclusion criteria:

1. Previous thyroid surgery
2. Use of thyroid medications before treatment
3. Presence of severe concomitant endocrine pathology

The functional state of the thyroid gland was assessed by determining serum levels

of thyroid-stimulating hormone (TSH), free thyroxine (fT4), free triiodothyronine (fT3), and antibodies to thyroid peroxidase (anti-TPO). The studies were performed using enzyme-linked immunosorbent assay.

The structural state was evaluated using ultrasound with determination of gland volume, echogenicity, parenchymal homogeneity, presence of nodular formations, and signs of autoimmune process.

Statistical analysis was performed using SPSS 16.0. Quantitative indicators are presented as $M \pm SD$. Student's t-test was used for group comparison. Differences were considered statistically significant at $p < 0.05$.

Results

Group 1 – surgical treatment + adjuvant chemotherapy.

Group 2 – neoadjuvant + adjuvant therapy. Data are presented as mean $\pm$ standard deviation.

p – significance of differences between the main groups and the control group.

Table 1. Thyroid hormonal profile parameters in examined patients ($M \pm SD$)

Parameter	Group 1 (n=62)	Group 2 (n=74)	Control (n=23)	p
TSH (mIU/L)	5.9 ± 1.0	7.2 ± 1.3	3.18 ± 0.48	<0.0001
fT4 (pmol/L)	6.0 ± 0.70	5.4 ± 0.60	8.73 ± 0.63	<0.0001
fT3 (pmol/L)	2.1 ± 0.18	1.7 ± 0.20	4.6 ± 0.25	<0.0001

In patients of both main groups, a statistically significant increase in TSH level and a decrease in concentrations of fT4 and fT3

were revealed compared to the control group ($p < 0.0001$). The most pronounced changes were registered in the second group.

Table 2. Frequency of thyroid functional disorders (%)

Parameter	Group 1 (n=62)	Group 2 (n=74)	Control (n=23)
Elevated TSH	33.9%	55.4%	8.7%
Decreased fT4	40.3%	62.1%	—
Decreased fT3	38.7%	55.4%	—
Elevated anti-TPO	14.5%	13.5%	4.3%

Comparative analysis demonstrated a statistically significant increase in the frequency of thyroid functional disorders in patients receiving combined therapy compared to the control group ($p < 0.05$).

In the second group, an increase in TSH level was registered in 55.4% of patients, which significantly exceeded the indicators of both the first group (33.9%) and the control (8.7%).

A decrease in fT4 was detected in 62.1% of patients in the second group and in 40.3% in the first group, whereas such changes were not observed in the control group ($p < 0.05$).

A similar trend was established for fT3: a decrease was registered in 55.4% of patients in the second group and in 38.7% in the first group, with no cases in the control group ($p < 0.05$).

The frequency of elevated anti-TPO in the main groups (14.5% and 13.5%) did not differ significantly between them, but exceeded the control group (4.3%), which may indicate a possible immunological component of the detected disorders.

Thus, a significantly higher prevalence of laboratory signs of hypothyroidism was revealed in the second group, confirming the cumulative and dose-dependent nature of the effect of combined anticancer therapy on thyroid function.

Table 3. *Ultrasound characteristics of the thyroid gland (%)*

Parameter	Group 1 (n=62)	Group 2 (n=74)	Control (n=23)	P
Diffuse decrease in echogenicity and heterogeneity	40.3%	40.5%	8.7%	<0.01
Normal echostructure	45.2%	44.6%	87.0%	<0.01

Analysis of ultrasound characteristics of the thyroid gland demonstrated significant differences between the main and control groups.

Diffuse decrease in echogenicity and heterogeneity of the parenchymal structure were detected in 40.3% of patients in the first group and 40.5% in the second group, which is more than four times higher than in the control group (8.7%; $p<0.01$).

No statistically significant differences were found between the first and second

groups for this parameter ($p>0.05$), indicating a similar frequency of structural changes regardless of the sequence of chemotherapy.

Normal thyroid echostructure was significantly more often observed in the control group (87.0%) compared to the first (45.2%) and second (44.6%) groups ($p<0.01$).

The obtained data indicate a high prevalence of structural changes of the thyroid gland in patients receiving combined treatment for breast cancer.

Table 4. *Frequency of symptoms (%)*

Symptom	Group 1	Group 2	Control
Fatigue	87.1%	83.8%	26.1%
Dry skin	61.3%	54.1%	13.0%
Drowsiness	54.8%	47.3%	8.7%
Edema	41.9%	35.1%	4.3%
Weight gain	35.5%	33.8%	8.7%

Clinical analysis showed that symptoms characteristic of hypothyroidism were significantly more often observed in patients undergoing combined treatment compared to the control group ($p<0.05$).

The most pronounced manifestation was general weakness and increased fatigue, observed in more than 80% of patients in both main groups, whereas in the control group this symptom was recorded only in about one quarter of cases.

Dermatological manifestations such as dry skin were registered in more than half of the patients in the main groups, significantly exceeding the control group.

A similar pattern was observed for drowsiness, the frequency of which in the treat-

ment groups exceeded the control values more than fivefold.

Peripheral edema and weight gain were also significantly more frequent in patients receiving anticancer therapy, while in the control group these symptoms were rare.

No statistically significant differences were found between the first and second groups ($p>0.05$), indicating a similar clinical severity of hypothyroid syndrome regardless of treatment stage.

Thus, clinical data confirm the development of a typical hypothyroid symptom complex in patients undergoing combined treatment for breast cancer.

Discussion

The obtained results indicate the development of persistent thyroid dysfunction in patients undergoing combined treatment for breast cancer. The observed changes are systemic in nature and are confirmed by a combination of laboratory, ultrasound, and clinical data.

An increase in TSH levels combined with a decrease in free thyroxine and triiodothyronine levels indicates the predominance of primary hypothyroidism. More pronounced hormonal changes in the second group suggest a cumulative effect of cytotoxic therapy. It is likely that the sequential use of neoadjuvant and adjuvant therapy increases the load on the hypothalamic-pituitary-thyroid axis, contributing to the exhaustion of compensatory mechanisms.

The absence of significant differences in ultrasound changes between the first and second groups suggests that structural alterations develop at early stages of systemic therapy and persist regardless of treatment sequence. Decreased echogenicity and parenchymal heterogeneity may reflect both dystrophic processes and subclinical inflammation.

The immunological component, reflected by moderate elevation of anti-TPO, does not appear to be dominant; however, its presence in some patients suggests a possible role of immune mechanisms in the pathogenesis.

Clinical symptoms generally correspond to laboratory findings, although their severity does not always directly correlate with

hormone levels, highlighting the multifactorial nature of symptoms in oncology patients.

Overall, the results confirm that thyroid dysfunction is a frequent manifestation of endocrine toxicity of combined breast cancer treatment.

Conclusions

1. Patients with breast cancer receiving combined treatment develop significant thyroid dysfunction characterized by increased TSH and decreased fT4 and fT3.
2. The frequency of laboratory signs of hypothyroidism exceeds 60%.
3. Neoadjuvant treatment regimens are associated with more pronounced hormonal changes, suggesting a cumulative and dose-dependent effect.
4. Ultrasound signs of structural thyroid changes are observed in a significant proportion of patients.
5. Clinical manifestations of hypothyroidism are significantly more frequent in treated patients but do not always correspond to laboratory findings.
6. Monitoring of thyroid function and ultrasound assessment should be included in follow-up protocols.
7. Further studies are required to evaluate long-term effects and their impact on treatment outcomes.

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Sources of funding: *The work did not receive any specific funding.*

Conflict of interest: *The authors declare no explicit or potential conflicts of interest associated with the publication of this article.*

Contribution of the authors;

Azimova A. Makhbuba - editing the article, writing the text
Nasirova K. Khurshidakhon - ideological concept of the work
Kurbanov B. Daniyar - ideological concept of the work

submitted 19.05.2026;

accepted for publication 03.06.2026;

published 30.06.2026

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Section 4. Technical sciences in general

DOI:10.29013/AJT-26-5.6-83-89



TECHNOLOGY INCUBATOR FOR STARTUPS. (Technology incubator as an organizational framework within an ecosystem for the effective implementation of an innovation-driven development model for industrial and agricultural production)

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Cite: Kamaletdinova A. (2026). *Technology Incubator for Startups. (Technology incubator as an organizational framework within an ecosystem for the effective implementation of an innovation-driven development model for industrial and agricultural production)*. Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-83-89>

Abstract

The article examines the role of technology incubators as an organizational solution within an innovation ecosystem for the effective implementation of innovation-driven development in industrial and agricultural production. Particular attention is paid to the organizational principles that enable the transformation of innovative ideas into commercially viable technologies and market-ready products through structured incubation, technology transfer, and interdisciplinary collaboration. The publication provides an overview of the historical evolution of technology incubators, their organizational framework, and their contribution to accelerating innovation processes in industrial and agricultural sectors. Special emphasis is placed on the integration of advanced technological infrastructure, including testing laboratories, quantum computing technologies, augmented reality visualization, standardization mechanisms, and ecosystem-based management approaches that support the commercialization and scaling of innovative solutions.

The article emphasizes that technology incubators constitute an effective organizational mechanism for strengthening innovation ecosystems by facilitating the development, validation, and market implementation of new technologies. Their application contributes to enhancing the competitiveness, technological modernization, and sustainable development of industrial and agricultural production through the efficient transfer of knowledge and innovative technologies.

Keywords: *Technology incubator; Ecosystem; Effective implementation; Innovation-driven development model for industrial and agricultural production; Structural architecture of the ecosystem framework; Quantum computer; Augmented reality visualization; Testing*

laboratories; Laws of technical systems evolution; Standardization; Technology transfer

Introduction

The rapid development of innovation ecosystems and digital technologies has significantly increased the demand for advanced computational tools capable of supporting the analysis, modeling, and commercialization of complex technical systems. The grow-

ing complexity of industrial and agricultural production, combined with the integration of artificial intelligence, artificial neural networks, and emerging quantum computing technologies, requires fundamentally new organizational and methodological approaches to innovation management.

Figure 1. *Example of a startup employee's workstation*



One of the key challenges in the development of high-technology projects is the ability to perform rapid multidimensional analysis of technical, commercial, and patent-related information throughout the innovation life-cycle. Conventional computational methods often provide insufficient processing speed and analytical depth for evaluating multiple design alternatives, forecasting technology evolution, and selecting optimal commercialization strategies. Recent advances in quantum computing have demonstrated the potential to overcome these limitations by enabling substantially more efficient processing of complex multidimensional datasets and system interactions.

At the same time, the increasing complexity of modern technical systems highlights the need to reconsider the traditional principles governing technological evolution. Classical methodologies, including the Theory of Inventive Problem Solving (TRIZ), provide a valuable foundation for innovation analysis; however, they do not fully reflect the multidisciplinary nature of contemporary innovation ecosystems, where techni-

cal, economic, organizational, and commercial factors are closely interconnected. The emergence of quantum computing and intelligent analytical technologies creates new opportunities for revising the principles of innovation management and integrating technical system evolution with technology transfer, commercialization processes, and ecosystem-based development models.

The present study is based on the assumption that the effective development of innovation ecosystems requires a comprehensive analytical framework capable of simultaneously considering technological, organizational, economic, and commercial parameters. Such an approach enables more accurate identification of development pathways, optimization of innovation strategies, and acceleration of the transformation of scientific ideas into commercially successful technologies.

From the perspective of investors and project managers, the successful implementation of innovation projects requires a comprehensive analytical framework capable of evaluating how the formulation of an inventive prob-

lem influences the commercial potential of the resulting technological solution. Accurate definition of project objectives and systematic analytical modeling are essential for assessing development pathways, commercialization strategies, and the effectiveness of intellectual property protection. An incorrect formulation of research objectives may lead to inefficient resource allocation, reduced commercialization potential, and insufficient patent protection against unauthorized replication.

The development of innovation projects therefore requires a multidisciplinary approach that integrates technological analysis, patent strategy, licensing, and commercialization throughout all stages of the innovation lifecycle. This approach forms the basis for strategic decision-making and enables the effective transformation of scientific and engineering ideas into competitive industrial products.

Technology incubators represent the organizational infrastructure that supports this process by providing financial, scientific, and managerial resources required for the development of innovative projects. In many countries, these organizations operate under the supervision of ministries responsible for industry, trade, and, where appropriate, agriculture. Dedicated governmental fund-

ing mechanisms are typically established to support both innovation projects and the professional management of technology incubators, ensuring sustainable development and efficient allocation of public investment.

An important element of this organizational model is the involvement of highly qualified scientific and technical experts responsible for the evaluation, selection, and continuous monitoring of innovation projects. Their expertise contributes to maintaining high scientific standards, improving investment efficiency, and supporting informed decision-making throughout project implementation.

Technology incubators also maintain close cooperation with export promotion organizations and national standardization institutes. Export support institutions facilitate international market entry by providing methodological assistance, commercialization support, grant funding, and promotion of innovative products in global markets. At the same time, collaboration with standardization and testing organizations ensures compliance with international technical standards through advanced laboratory testing and certification procedures, thereby increasing the competitiveness and export potential of innovative technologies.

Figure 2. *Example of an integrated startup workstation*



Commercial testing laboratories constitute an important component of the innovation ecosystem alongside national standardization institutes. These laboratories provide independent testing and certification services in accordance with regional and international technical standards, including those that may differ from the standards adopted in the country where the innovation is being developed. Their involvement enables technology developers to evaluate product compliance with the regulatory requirements of target export markets at the early stages of product development.

Collaboration between technology incubators and commercial testing laboratories significantly reduces the risks associated with

international commercialization by identifying potential regulatory and technical barriers before market entry. This approach facilitates the adaptation of innovative products to local technical requirements and improves their readiness for global commercialization.

Another important element of the innovation ecosystem is cooperation with state-owned infrastructure companies and natural monopolies. In many countries, including Kazakhstan, strategically important infrastructure facilities are managed by government-owned enterprises that establish mandatory technical and operational requirements for products intended for use within national infrastructure systems.

Figure 3. *Example of an innovative startup development: an automated production and assembly line for microelectronic components*

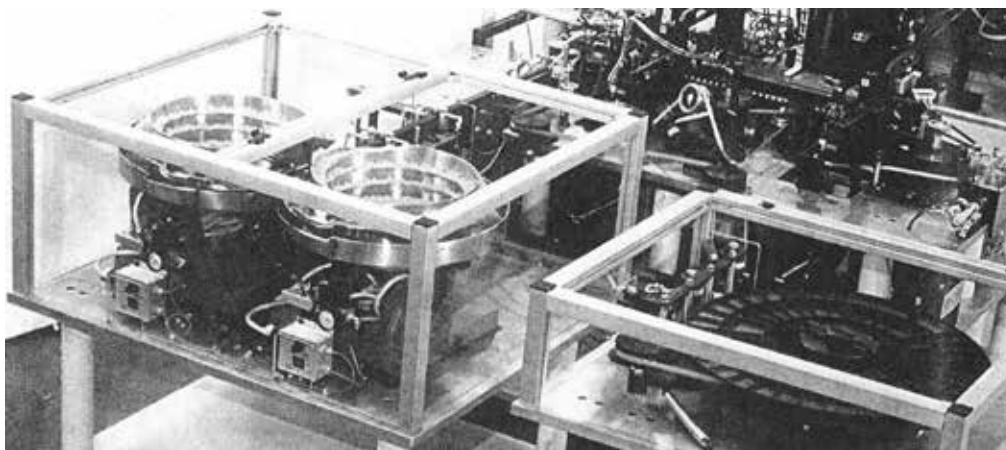
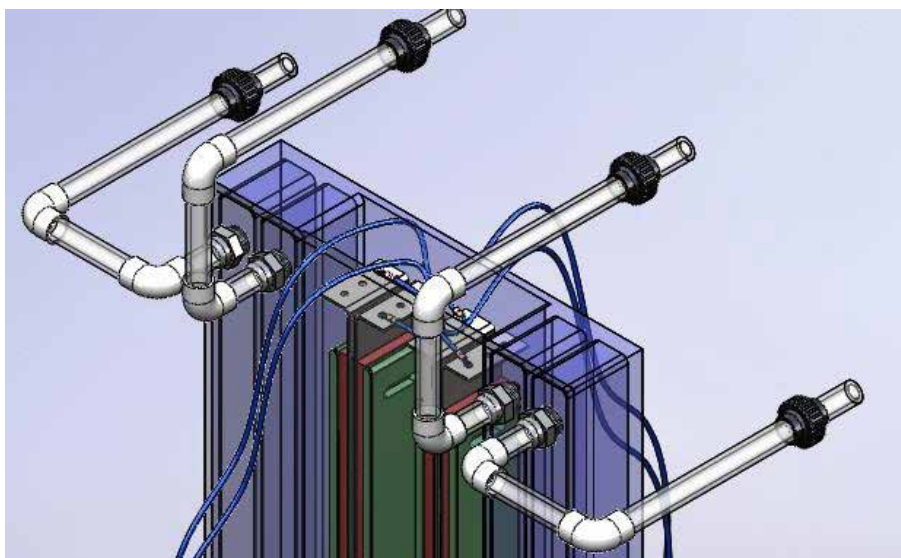


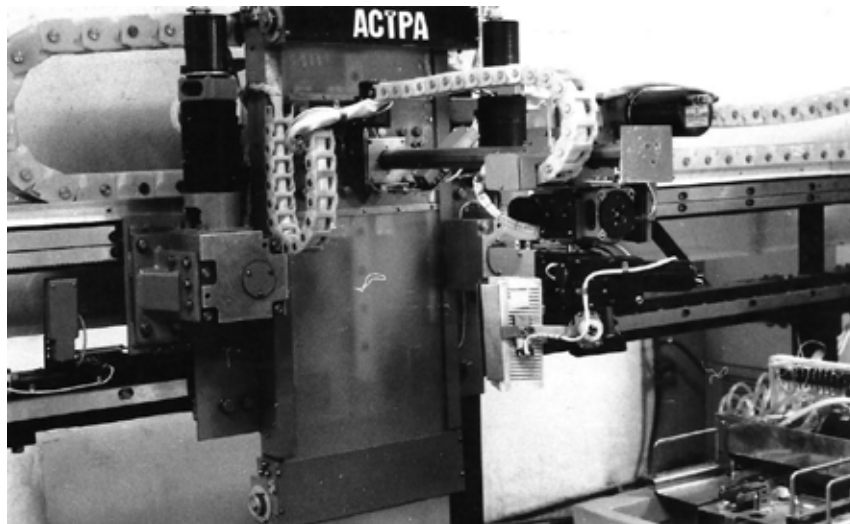
Figure 4. *Example of a startup-developed electrochemical reactor for maintaining the operational cycle of infrastructure components incorporating artificial intelligence and artificial neural network technologies within control and monitoring processors*



When an innovation project is associated with such infrastructure facilities, technology incubators establish close cooperation with these organizations to ensure technical compatibility, regulatory compliance, and successful implementation. Depending on the technical and commercial objectives of the project, state-owned companies may par-

ticipate as strategic partners or provide the regulatory and technical guidance necessary for the development and commercialization of innovative technologies. This collaborative approach minimizes implementation risks and facilitates the integration of new technologies into existing industrial and infrastructure systems.

Figure 5. *Example of a startup-developed flexible manufacturing module for photolithography on thin-film microcircuit substrates*



Intergovernmental and regional investment funds

Technology incubators make full use of available funding opportunities to ensure the timely financial support of innovation projects. For this purpose, numerous regional and international investment organizations – including European and North American funding programs, as well as specialized financial institutions such as the European Bank for Reconstruction and Development (EBRD)—provide financial support for collaborative research, technology development, and innovation projects.

Since each funding organization applies its own evaluation criteria and eligibility requirements, technology incubators incorporate these requirements into their project management processes from the earliest stages of company formation. This approach enables startup companies to become investment-ready and facilitates access to additional financing during subsequent stages of project development.

Municipal authorities

Technology incubators are frequently located in municipalities where they represent important sources of employment and regional economic development. Consequently, local authorities actively cooperate with incubator management by providing organizational, administrative, and infrastructure support within their areas of responsibility. During the establishment of new startup companies, technology incubators therefore create the organizational and logistical foundations necessary for effective collaboration with municipal institutions.

Professional associations

Professional organizations, including engineering, architectural, and other technical associations, actively contribute to innovation ecosystems by promoting collaboration between experienced professionals and startup companies. In particular, retired specialists frequently provide mentoring, technical expertise, and practical guidance, transferring valuable industrial and commercial

experience to innovation projects whenever appropriate.

Technical universities

Many universities have established their own technology incubators to support promising projects initiated by students, researchers, and academic staff. University-based incubators generally operate under organizational principles similar to those of independent technology incubators while benefiting from direct access to university laboratories, research facilities, and scientific expertise. These resources create favorable conditions for the development, validation, and commercialization of innovative technologies.

Multinational corporations

Large multinational corporations possess substantial financial, technological, and manufacturing resources that enable the rapid commercialization and industrial implementation of innovative technologies. Their participation in innovation ecosystems is naturally driven by strategic commercial interests; however, their contribution to technological advancement and the development of technology incubators remains highly significant. The specific mechanisms of collaboration between technology incubators and multinational corporations represent an important subject for further investigation.

Selection of ideas for project formation

Modern technology incubators typically specialize in specific technological sectors, although during the early stages of their development many incubators supported projects from multiple industrial fields. Increasing specialization, together with the partial or complete privatization of many incubators, has resulted in more systematic project evaluation and selection procedures. This has improved the identification of projects with strong commercialization potential while allowing technically promising but commercially weak concepts to be recognized at an early stage. As a result, financial resources can be concentrated on innovations with greater market potential, significantly improving investment efficiency.

Support mechanisms during the initial stages of project development

Technology incubators are designed to provide startups with favorable conditions during the earliest phases of innovation development. Their operational policies include financial, organizational, and managerial support mechanisms that reduce initial project risks and accelerate technology maturation. One common example is the provision of an advance payment amounting to approximately 10% of the total project funding, enabling newly established companies to recruit qualified specialists and initiate development activities immediately after project approval.

International industrial exhibitions and their impact on successful project commercialization

International industrial and technology exhibitions provide one of the most effective environments for benchmarking innovative products and technologies developed within technology incubators. These exhibitions enable comprehensive comparison of technical performance, commercial potential, market competitiveness, and consumer value against existing domestic and international solutions.

The evaluation of competing technologies presented at such exhibitions constitutes an essential responsibility of commercialization specialists. The quality of this analysis directly influences strategic decision-making regarding product positioning, technology development, and market entry. Accurate competitive assessment increases the likelihood of commercial success, whereas inadequate analysis may lead to ineffective development strategies and reduced market competitiveness.

Technology transfer

Technology incubators frequently serve as platforms for international collaborative research and innovation projects involving academic institutions, industrial partners, and governmental organizations. International technology transfer facilitates the exchange of scientific knowledge, engineering expertise, intellectual property, and advanced technological solutions, thereby accelerating the

commercialization of innovative products and strengthening global innovation ecosystems.

The proposed model of international cooperation between technology incubators is intended primarily for early-stage innovation projects seeking organizational, technological, and financial support. It does not apply to projects that are already fully financed or implemented within established industrial enterprises, nor to technologies that have already been transferred to existing innovation companies for commercialization.

Within this framework, the activities of technology incubators are organized in two complementary directions: support for domestic innovation projects within the host country and the development of international partnerships aimed at expanding research

cooperation, facilitating technology transfer, and promoting access to global markets.

Given the rapidly growing demand for intelligent technologies incorporating artificial intelligence and artificial neural networks, numerous national governments have introduced specialized programs supporting research and innovation in these fields. In particular, strategic initiatives have been established to promote open artificial intelligence research, secure and privacy-preserving AI technologies, collaborative software and AI development, and educational and workforce training programs. Such initiatives create favorable conditions for international cooperation and accelerate the development and commercialization of advanced digital technologies within technology incubators.

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submitted 18.05.2026;

accepted for publication 02.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-90-95



**ACHIEVING THE IDEAL END RESULT WHEN USING
ACTIVATED CARBON-CARBON FABRICS
(Achieving the ideal end result in medicine through
the use of activated carbon-carbon fabrics and their
innovative modifications in modern treatment processes
and medical equipment, including integrative versions)**

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Cite: Amanova A.S. (2026). *Achieving the ideal end result when using activated carbon-carbon fabrics. (Achieving the ideal end result in medicine through the use of activated carbon-carbon fabrics and their innovative modifications in modern treatment processes and medical equipment, including integrative versions). Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-90-95>

Abstract

The article examines approaches to achieving the ideal final result in medicine through the use of innovative materials, particularly activated carbon-carbon fabrics and their advanced modifications, as well as modern computer modeling, artificial intelligence, and artificial neural networks. It is shown that the effective implementation of innovations requires the harmonious integration of new materials and technologies with established medical solutions, ensuring continuity, safety, and stability of treatment processes. Special attention is given to the principles of systemic and combinatorial design presented in the scientific and technological works of Gulmira Kenzhebayeva, which focus on the adaptation of innovative materials within existing healthcare infrastructures.

Keywords: *Ideal final result; Activated carbon–carbon fabrics; Achieving the ideal final result in medicine; Activated carbon–carbon fabrics and their innovative modifications in modern treatment processes and medical equipment, including integrative versions of smart family physician office equipment*

The article presents examples involving natural and composite materials, including zeolites and carbon-carbon composites, for the development of new medical devices, instruments, and auxiliary equipment with improved performance characteristics. Emphasis is placed on the role of computer

modeling and digital design in optimizing material properties, enhancing treatment effectiveness, and supporting the development of next-generation medical technologies.

The field of innovation is typically saturated with traditionally used technical solutions and materials; therefore, innovative changes

of all types must be adapted to and integrated with existing technologies and materials as a condition of successful implementation.

Figure 1.

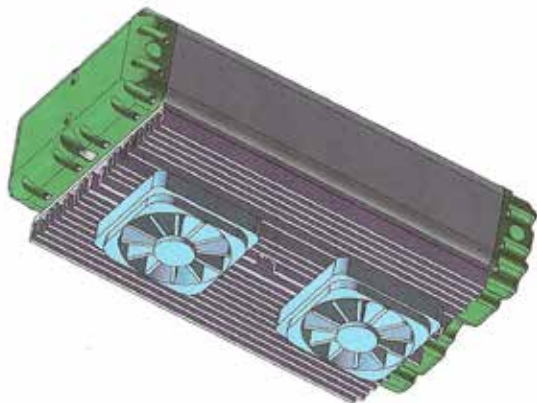
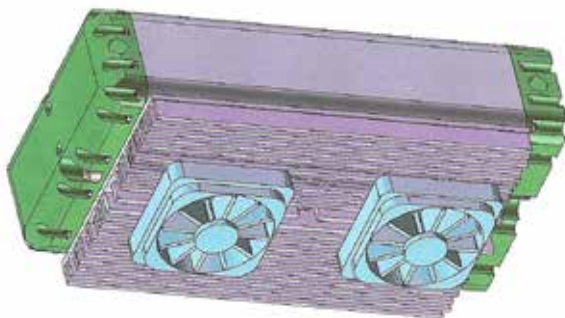
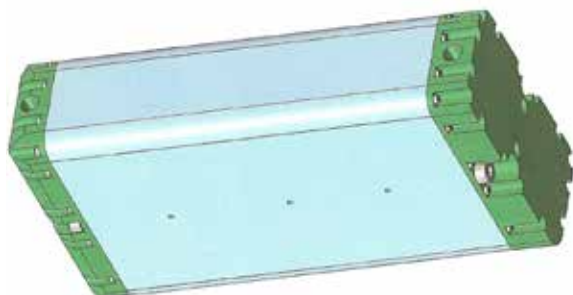


Figure 2.



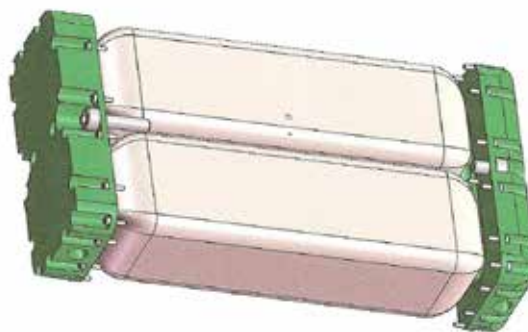
In infrastructure and foundational solutions, including those serving auxiliary functions, the correct, coordinated, and harmonious integration of system elements is of critical importance.

Figure 3.



System interactions at all levels largely determine the success of the innovation process in conjunction with the overall infrastructure and the design architecture of equipment and specialized instruments.

Figure 4.

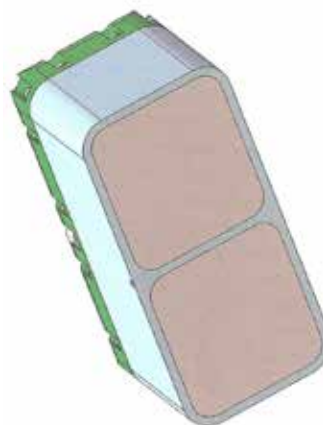


Overall, innovation is not an end in itself. The central objective of the entire innovation process is to achieve a final outcome from the implementation of innovative ideas at a level that enables a qualitative improvement of all treatment process parameters while preserving the continuity of equipment, technologies, materials, and consumables.

In this publication, the author intends to examine several practical relationships among these elements and analyze the fundamental methods and approaches for adapting innovative solutions and materials within the structure and interdependencies of traditionally used technologies, techniques, and materials.

Until recently, the innovation process was largely driven by specialists in medical technologies and materials who often lacked sufficient experience in computer modeling and process simulation. As a result, implementation decisions were primarily based on positive testing and research outcomes.

Figure 5.



For a considerable period, dialogue between conservative-minded specialists and innovators was often lengthy and not always

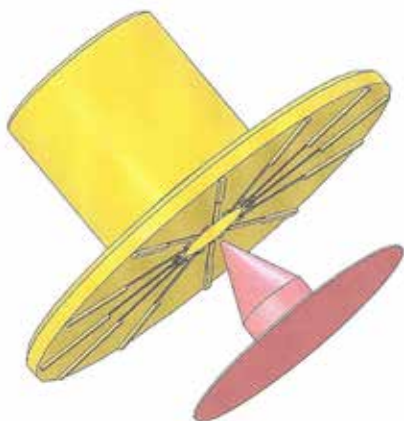
successful, frequently to the disadvantage of the innovators. Practitioners remained in search of solutions that could clearly demonstrate practical and effective pathways for implementing innovations without causing significant disruption to the stability of established technological processes.

To the credit of advocates of innovative technological transformation, it should be noted that in recent years several comprehensive solutions have emerged that enable the seamless implementation of innovative technologies under the real conditions of modern medical science and practice, as well as in other scientific and applied fields.

The author of this publication finds that, within her methodology and analytical approach, Gulmira Kenzhebayeva considers comprehensive integrative solutions to be the most effective approach, as reflected in the proposals presented in her scientific and technological publications and books.

What particularly distinguishes these proposals and developments from similar works by other authors is the broad platform they provide for experimental computer modeling. This capability is based on Gulmira Kenzhebayeva's extensive and multidisciplinary knowledge of the fundamental principles and methods of systems-based and combinatorial computer modeling applied to related innovation processes, including those at the intersection of key scientific and technological disciplines.

Figure 6.



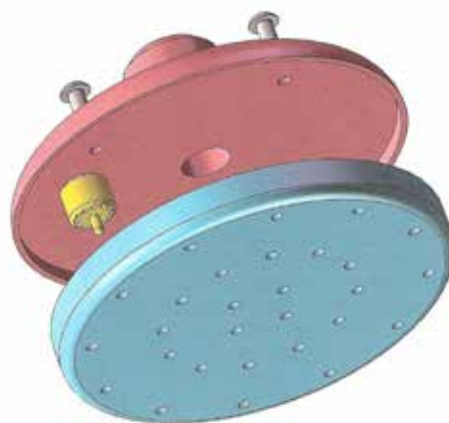
In analyzing the 11 innovative medical technologies presented in her publications, Gulmira Kenzhebayeva advances a thesis of

particular importance for addressing this challenge – the combinatorial structure of each solution. This concept is based on the harmonious integration and mutual complementarity of traditional technologies and materials with innovative technologies and materials, primarily composite materials.

Among Gulmira Kenzhebayeva's proposals, the most significant aspect is the emphasis on the integration and comprehensive adaptation of new materials and technological approaches within the environment of existing, proven technologies and materials. This approach creates a foundation for transforming their properties and capabilities to a new, innovative level.

The adoption of these principles has made it possible to take into account the potential for the further development of materials, designs, and technological methods, enabling a smooth transition, for example, from flexible, permeable, and volumetrically porous systems and materials to solid materials that retain similar chemical compositions and fundamental properties.

Figure 7.



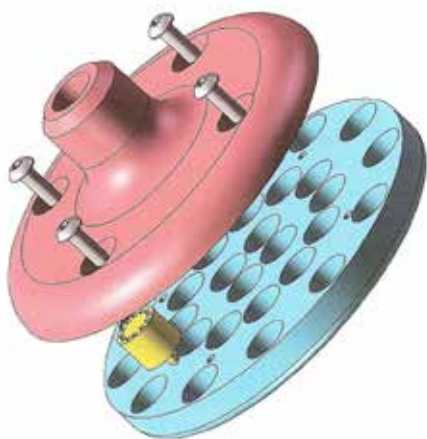
Furthermore, this fundamental approach to the application of new composite materials in novel medical applications with unique properties and characteristics makes it possible to develop new medical devices and instruments that meet the demanding requirements of modern healthcare technologies.

It is also important to recognize that, in addition to advanced composite materials, nature provides exceptionally valuable natural materials. The approaches outlined in Gulmira Kenzhebayeva's publications make

it possible to create a harmonious combination of well-known natural materials and extensively validated engineering and technological methods.

The image presented at the beginning of this publication illustrates such an application through the use of the natural aluminosilicate mineral zeolite in the laboratory preparation of water, for example, for cleansing the surface of a patient's body prior to subsequent medical treatment procedures.

Figure 8.

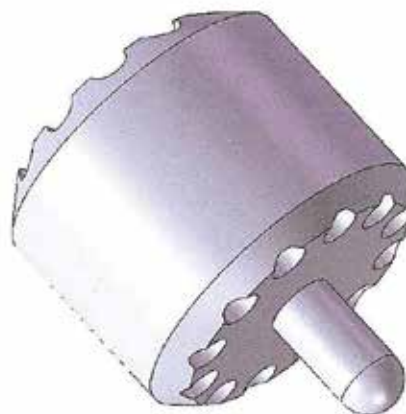


The presented models demonstrate that, by applying the general principles of innovative design proposed by Gulmira Kenzhebayeva, it is possible to achieve an almost ideal final result within a traditional form and structure – such as an ion-exchange filter – through the use of natural and completely safe materials. Such solutions can provide unique characteristics and performance advantages, including:

- The complete elimination of chemical reagents from the process.
- The utilization of the natural ion-exchange properties of zeolite.
- The exceptionally high ion-exchange capacity of zeolite, including its potential for the purification of radioactively contaminated liquids.

These design approaches fundamentally transform the requirements placed on the design process itself, creating opportunities for the extensive integration of computer modeling methods and simulation techniques into the development and optimization of innovative solutions.

Figure 9.



The conceptual solutions proposed by Gulmira Kenzhebayeva make it possible to further develop carbon-carbon composites, for example by transforming carbon-carbon fabrics into compressed solid components with unique properties that open new opportunities for innovation in medical and related applications.

One of the key advantages of these materials is their exceptionally high temperature resistance, with the potential to operate at temperatures of up to 4000 °C. Disinfection at such temperatures makes it possible to reliably eliminate bacteria, viral agents, and other forms of contamination from medical instruments and equipment.

Figure 10.



The following design models feature massage heads in which all components, including the massage plungers, are manufactured from compressed carbon-carbon fabric composites. This design approach is charac-

terized by the ability to combine the novel properties and performance characteristics of advanced materials with traditional materials and established methods of application within a unified systems-design framework.

The fundamental possibility of developing technical solutions of this kind emerged through the application of the principles of combinatorial design and software-driven selective modeling of innovative materials, their integrative combinations, and modifications, as outlined in the publications of Gulmira Kenzhebayeva. These principles were incorporated throughout all stages of the project development process.

As an example, the author presents a design concept based on Bernoulli principles and effects for localized vortex cleaning systems intended for the preparation of a patient's body surface prior to medical intervention. The components of the proposed device are manufactured from the same compressed carbon-carbon composite material discussed above, enabling highly effective cleaning and disinfection of contact elements.

Although only a limited number of examples are presented, they clearly demonstrate the validity of these design approaches and the principles of material selection, providing a foundation for the further modification, optimization, and enhancement of material properties and functional capabilities.

Figure 11.



As demonstrated by design practice, for devices and systems that can be classified as auxiliary medical equipment, accessories,

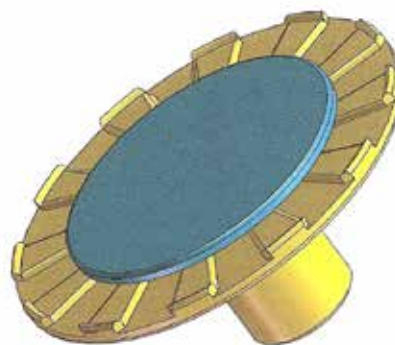
and instruments, it is most effective to utilize modern versions of the SolidWorks engineering design software suite during the development process.

The software already incorporates capabilities for structural analysis of design quality and performance. The accumulated data and integrated parameters can be effectively applied in parallel computer modeling processes to evaluate and verify the validity of proposed design solutions.

Furthermore, when all necessary technical requirements, specifications, and local standards are available, specific critical requirements and control parameters embedded within SolidWorks make it possible to utilize the software's internal analytical capabilities for more detailed computer modeling during the so-called late design stages.

When every component of a design serves not merely a decorative function but plays a critical role in ensuring the proper operation of a device, instrument, or piece of equipment, SolidWorks enables detailed local modeling of individual components as well as assemblies consisting of multiple functionally interconnected parts.

Figure 12.



Another factor that significantly facilitates both the setup and selective processes of computer modeling is the use of engineering design software rather than purely graphical programs during the design stage.

The author intends to devote future publications to a more detailed discussion of this topic.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-96-101



DEVELOPMENT OF ENVIRONMENTALLY CLEAN MOTOR FUELS BASED ON A MIXTURE OF SYNTHETIC AND TRADITIONAL HYDROCARBONS AND THEIR PHYSICAL AND CHEMICAL ANALYSIS

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Cite: Ruziev A. T., Mavlonov Sh. B., Saloydinov A. A. (2026). *Development of Environmentally Clean Motor Fuels Based on a Mixture of Synthetic and Traditional Hydrocarbons and Their Physical and Chemical Analysis. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-96-101>

Abstract

This study investigates the physicochemical and performance properties of blended fuels obtained by compounding synthetic diesel fuel produced at the Uzbekistan GTL plant with conventional EURO K4 diesel fuel at blending ratios of 50–60%. The results showed that the cetane number of the blends ranged from 62 to 63, while the cetane index was 59.5–60.0. Fuel density varied between 791.2 and 796.1 kg/m³, and kinematic viscosity at 40 °C was in the range of 3.27–3.33 mm²/s. The cold filter plugging point was found to be –10 to –11 °C, indicating improved low-temperature performance due to the addition of synthetic components. Sulfur content ranged from 9.4 to 17.2 mg/kg, meeting environmental requirements. Flash point values were 71–75 °C, wear scar diameter was 450–460 μm, and oxidation stability sediment content was 3.3–3.7 g/m³. The obtained results confirm that scientifically based blending of synthetic GTL components with petroleum diesel fractions is a promising approach for producing environmentally friendly and high-performance motor fuels.

Keywords: GTL, synthetic diesel fuel, fuel blending, cetane number 62–63, density 791–796 kg/m³, low-temperature properties, sulfur content 9–17 mg/kg, oxidation stability

Introduction:

Currently, the issue of producing environmentally friendly and highly efficient automotive fuels in the fuel and energy sector is one of the most pressing scientific directions on a global scale (International Energy Agency (IEA). *World Energy Outlook 2022*). The increase in the number of vehicles, the expansion of industrial production volumes, and the increase in harmful emissions into

the atmosphere necessitate the improvement of the quality indicators of traditional petroleum fuels (European Environment Agency. *Transport and Environment Report*. 2021). At the same time, the tightening of international environmental standards requires the creation of a new generation of fuels with high energy efficiency that release fewer harmful substances during combustion. In solving these tasks, the technology for pro-

ducing synthetic liquid fuels based on natural gas, specifically the Gas-to-Liquids (GTL) process, is of great scientific and practical importance (Dry M. E. Fischer–Tropsch synthesis and the production of clean fuels. 2002).

In recent years, numerous scientific studies have been conducted on the composition, physicochemical properties, and impact on engine performance and environmental indicators of products obtained using GTL technology (Chevron Corporation. 2004). Scientific literature extensively highlights the high cetane number of synthetic diesel fuels, their very low content of sulfur and aromatic hydrocarbons, and the stability of the combustion process (Chevron Corporation. 2004). There are also scientifically grounded results regarding the possibility of optimizing fuel performance, improving engine operating modes, and reducing harmful emissions by combining GTL products with traditional petroleum fractions (ExxonMobil. *Blending of GTL Diesel with Conventional Diesel Fuel*. 2013)]. Some studies have shown that by selectively mixing narrowly fractionated components, it is possible to control the low-temperature properties of diesel fuels, optimize density and viscosity, and increase combustion efficiency (Lapuerta M., Armas O., García-Contreras R., 2009).

However, existing scientific research does not sufficiently cover the comprehensive study of the regional characteristics of GTL products, particularly the specifics of the composition of synthetic fuels produced at the “Uzbekistan GTL” plant. At the same time, the scientific and technological foundations for obtaining environmentally friendly fuels with improved low-temperature properties based on the compounding of these products with traditional petroleum fractions in optimal ratios have not been fully developed. In particular, scientific results have not been obtained on controlling the composition of

mixed fuels based on narrowly fractionated hydrocarbon components, determining the relationship between their physicochemical and environmental indicators, and creating fuel compositions that meet international standards.

Accordingly, the main objective of this study is to conduct a comprehensive analysis of the physicochemical properties of “Uzbekistan GTL” products and to develop fuel compositions with improved environmental and operational properties based on their compounding with narrow fraction components derived from oil. To achieve this goal, the following tasks have been defined:

- Determination and assessment of the main physicochemical indicators of synthetic GTL products;
- Studying the theoretical and technological foundations of the mixing process with petroleum fractions;
- identifying factors affecting the low-temperature properties, combustion efficiency, and environmental indicators of blended fuels;
- development of optimal compounding compositions and scientific substantiation of the prospects for obtaining environmentally friendly fuels.

Materials and methods:

Synthetic diesel fractions produced at the “Uzbekistan GTL” plant, as well as traditional diesel fractions from local oil refineries and narrowly fractionated hydrocarbon components, were used as the primary raw materials for the research work. All components used in the studies were selected in accordance with the requirements of current technical specifications and standards, and their initial physicochemical indicators were determined before the experiments began (Table 1).

Comparison of GTL synthetic diesel fuel and ECO diesel fuel performance

Table 1.

No. Indicator name	ECO diesel standard (O'zDSt 1134:2018)	ECO diesel (RVS-24, 09.02.2026)	GTL synthetic diesel (10.02.2026)
1. Number of sets, at least	50	57	83.5
2. Density at 20 °C, kg/m ³ , at most	860	832.5	771.5

No.	Indicator name	ECO diesel standard (O'zDSt 1134:2018)	ECO diesel (RVS-24, 09.02.2026)	GTL syn- thetic diesel (10.02.2026)
3.	Fractional composition: 50% distil- lation temperature, °C, maximum	280	262	268
	Fractional composition: 96% distil- lation temperature, °C, maximum	360	357	335
4.	Water content	shouldn't be	no	no
5.	Boundary filtration temperature, °C, at most	–5	–4	–25
6.	Iodine number, g/100 g of fuel, no more than	5	0.79	0.16
7.	Coking of a 10% residue, %, not more than	0.2	0.013	0.049
8.	Ash content, %, no more	0.01	0.0034	0.0057
9.	Mass fraction of sulfur, ppm, maxi- mum	0.10 (Type I) 0.05 (Type II) 0.01 (Type III)	0.097 – –	4.4 ppm – –
10.	Mercaptan sulfur content, %, not more than	0.01	0.0015	0.0005
11.	Hydrogen sulfide (H ₂ S) content	shouldn't be	no	no
12.	Copper plate test	Can withstand 1st class	Class 1	Class 1
13.	Water-soluble acids and alkalis	shouldn't be	no	no
14.	Kinematic viscosity at 20 °C, mm ² /s	3.0–6.0	4.0	3.7
15.	Acidity, mg KOH/100 cm ³ , no more	5	0.3	2.0
16.	Flash temperature, °C, at least	62	65	74
17.	Mechanical impurities, %, no more	0.0024	0.0012	0.0004
18.	Actual resins, mg/100 cm ³ , no more	40	17	3.0
19.	Hardening point, °C, maximum	–10	–8	–33
20.	Turbidity temperature, °C, at most	–5	–2	–22
21.	Lubrication (WSD at 60 °C), μm, at most	–	670	400
22.	Polycyclic aromatic hydrocarbons, %, not more than	–	–	0
23.	Oxidation stability (sediment), g/ m ³ , no more than	25	–	2.8

Materials:

The following main materials were used in the experimental studies: – synthetic diesel fuel (GTL diesel fraction), hydrotreated oil-gas condensate diesel fraction, narrow fractions of kerosene and gas oil, depressant additives (as necessary) for optimization to improve low-temperature properties during

the compounding process, standard reagents and solvents for laboratory testing.

The density, kinematic viscosity, cetane number, fractional composition, solidification temperature, filtration threshold temperature, sulfur content, and proportion of aromatic hydrocarbons of all fuel samples were determined in accordance with current

international and national standards, and a preliminary assessment was conducted.

Compounding method:

The preparation of fuel compositions was carried out under laboratory conditions using the mechanical compounding method. In this process, synthetic GTL fractions and oil-derived diesel components were mixed in predetermined proportions (volume or mass fractions). The mixing process was carried out in a thermostatic reactor with a constant mixer in the temperature range of 20–40 °C. Mixing was carried out for 15–30 minutes to ensure the homogeneity of the mixture.

During the compounding process, compositions in various ratios were prepared, and their physicochemical and operational indicators were compared. To determine the optimal composition, the proportion of the GTL component was gradually adjusted.

Physicochemical analysis methods:

The main quality indicators of the prepared fuel compositions were determined based on the following standard methods:

density was determined by the picnometric or areometric method, kinematic viscosity by capillary viscometer; fractional composition by standard distillation apparatus, cetane number by calculation or engine test methods (cetanometer); low-temperature properties (limit temperature of turbidity, solidification, and filtration) by cooling bath and special filter devices; sulfur content by X-ray fluorescence or chemical analysis methods; and combustion efficiency and environmental indicators by laboratory engine test bench.

Results and their discussion:

Table 2 presents the results of laboratory analyses of mixtures in which synthetic GTL diesel fuel was added to EURO K4 diesel fuel in various proportions at 60%, 55%, and 50%. As seen from the table, the increase in the proportion of the synthetic component had a significant impact on the main physicochemical and operational indicators of the fuel.

Results of laboratory analysis of EURO K4 diesel fuel and GTL synthetic diesel mixes

Table 2.

No.	Indicator name	Analysis method	EURO K4 diesel 40% + GTL 60%	EURO K4 diesel 45% + GTL 55%	EURO K4 diesel 50% + GTL 50%
1.	Number of sets, at least	ASTM D613	62	63	62
2.	Setan index, at least	ASTM D4737	60.0	60.0	59.5
3.	Density at 20 °C, kg/m ³	GOST 3900	791.2	793.1	796.1
4.	Fractional composition: distillation at 250 °C, % (vol.) at least	GOST 2177	44	43	44
	distillation at 350 °C, % (vol.) at least		97	96	96
	95% distillation temperature, °C, at most		335	342	340
5.	Water content, mg/kg, maximum	GOST 2477	42.8	44.5	43.7
6.	Boundary filtration temperature, °C, at most	EN 116	–10	–10	–11
7.	Coking of a 10% residue, %, not more than	ASTM D4530	0.018	0.016	0.018
8.	Ash content, %, no more	GOST 1461	0.0033	0.0030	0.0032
9.	Sulfur content, mg/kg, maximum	EN ISO 20884	9.4	11.3	17.2

No.	Indicator name	Analysis method	EURO K4 diesel 40% + GTL 60%	EURO K4 diesel 45% + GTL 55%	EURO K4 diesel 50% + GTL 50%
10.	Corrosion on a copper plate (3 hours, 50 °C)	ASTM D130	1a	1a	1a
11.	Kinematic viscosity at 40 °C, mm ² /s	GOST 33	3.27	3.31	3.33
12.	Flash point, °C, at least	GOST 6356	71	73	75
13.	Polycyclic aromatic hydrocarbons, %, not more than	EN 12916	2.9	3.4	3.8
14.	Total pollution, mg/kg, not more than	EN 12662	5.6	5.4	5.8
15.	Oxidation stability: sediment content, g/m ³ , no more	ASTM D2274	3.3	3.4	3.7
	Stability time, hours, at least		20	20	20
16.	Methyl esters of fatty acids (FAME), not more than %	GOST EN 14078	0.05	0.04	0.05
17.	Lubrication (WSD 1.4), at 60 °C, no more than μm	ASTM D6079	460	455	450

It has been established that changes in the proportion of synthetic components in blends based on EURO K4 diesel fuel and synthetic GTL diesel fuel significantly affect the main operational and environmental properties of the fuel. The cetane number in the mixtures was determined to be in the range of 62–63, indicating a high level of combustion efficiency for all samples, while the ethane index ranged from 59.5 to 60.0, with no sharp changes observed as the proportion of the synthetic component increased. The density indicators varied from 791.2 to 796.1 kg/m³, with an increase in density as the proportion of synthetic fuel decreased. According to the results of the fractional composition, the distillation fraction at 250 °C was 43–44%, and at 350 °C, it was 96–97%, while the 95% distillation temperature was recorded in the range of 335–342 °C, indicating that the evaporation properties of the mixed fuels are at the level of standard requirements. The threshold filtration temperature was determined to be within the range of minus 10–11 °C, and an improvement in low-temperature properties was observed in the mixture with a high proportion of synthetic components. The sulfur content was determined to be in the

range of 9.4–17.2 mg/kg, and it was established that all samples meet environmental requirements, while the proportion of polycyclic aromatic hydrocarbons is 2.9–3.8%, increasing as the proportion of synthetic components decreases. It was found that the kinematic viscosity at 40 °C ranges from 3.27 to 3.33 mm²/s, the flow properties of mixed fuels are at the required level, and the combustion temperature is in the range of 71–75 °C, which indicates high safety indicators for diesel fuels. According to lubrication indicators, the wear diameter ranges from 450 to 460 μm, which leads to an improvement in tribological properties as the proportion of synthetic components increases. Oxidation stability results showed that the precipitate content is 3.3–3.7 g/m³, confirming the chemical stability of mixed fuels during storage.

The results obtained show that by combining synthetic GTL diesel fuel with traditional EURO K4 diesel fuel, it is possible to purposefully control the physicochemical, environmental, and operational indicators of the fuel. The addition of a synthetic component with a high cetane number can lead to a faster and more complete combustion process, increasing engine efficiency and

reducing harmful emissions. Maintaining the fractional composition within the optimal range balances the fuel evaporation process, creating favorable conditions for complete oxidation within the combustion chamber. The low sulfur content is an important factor from an environmental perspective and serves to reduce the amount of SO_x compounds emitted into the atmosphere. Improving lubrication properties allows for a reduction in friction between engine parts and an increase in their service life. At the same time, the change in the proportion of polycyclic aromatic hydrocarbons depending on the composition of the mixture showed the need for further optimization of the fuel composition. The possibility of further improving the environmental and operational properties of blended fuels through the use of narrowly fractionated components and functional additives in the future-compounding synthetic GTL diesel fuel with petroleum-derived diesel fractions-can be evaluated as a promising technological direction for producing high-efficiency fuels that meet modern environmental requirements.

Conclusion:

The results of the conducted research showed that by combining synthetic GTL diesel fuel with traditional EURO K4 diesel fuel, it is possible to purposefully improve the main physicochemical, operational, and environmental indicators of the fuel. Maintaining a high cetane number in blended fuels ensures an efficient combustion process, contributing to increased engine productivity and a reduction in harmful emissions. Additionally, low sulfur content and high oxidation stability ensure the environmental safety of mixed fuels and their stability during the storage process. Improving lubrication properties helps to reduce the wear of engine parts and extend their service life. At the same time, certain indicators, in particular the proportion of polycyclic aromatic hydrocarbons, indicate the need for further optimization of the mixture composition. Overall, the scientifically grounded compounding of synthetic GTL diesel fuel with narrowly fractionated petroleum components is a promising technological direction for producing high-efficiency motor fuels that meet modern environmental standards, and it is advisable to conduct in-depth research in this direction in the future.

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submitted 14.05.2026;

accepted for publication 24.05.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-102-106



PERFORMANCE ANALYSIS OF MINERAL AND SEMISINTETIC, SYNTHETIC OILS USED IN GAS PREPASSION AGGREGATES

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Cite: Umarov, A.A., Ochilov, A.A., Saloydinov, A.A. (2026). *Performance Analysis of Mineral and Semisintetic, Synthetic Oils Used in Gas Prepassion Aggregates. Austrian Journal of Technical and Natural Sciences 2026, No 5–6.* <https://doi.org/10.29013/AJT-26-5.6-102-106>

Abstract

This article analyzes the thermal oxidation resistance and operational properties of mineral semi-synthetic and synthetic oils used in gas pumping units at three different temperatures, analyzes their effect on compressor oil by changing the flow part in SGT-400 gas pumping units, and as a result, it was determined that expanding the flow part of the impeller extends the oil's operating time and does not negatively affect quality indicators.

Keywords: oil, oxidation, mineral, semi-synthetic, synthetic, aviation fuel, temperature, density, optical density, logarithm

Mineral and semi-synthetic aviation fuel oils used in practice were selected for the study.

A graphical method was proposed, allowing for the analysis of the subsequent dependence using graphical model calculations without long-term experimental studies obtained after the oxidation resistance test of oils, which allows for a reduction in costs and time by reducing the testing time (Mohammad Maher Kallas, Mohammad Saed Al Sabek, and Younes Saoud. 2024).

This method is aimed at determining the optical density D , evaporability G , and the temperature change indicator P_{tos} .

To increase the oil testing time at the selected temperature and to analyze the oxidation stability indicators of the lubricant, the results obtained over the same time in-

terval are used. The decimal logarithm of the thermal energy absorbed by oxidation ND and evaporation products is then calculated (Kallas M. M., Sallam T., and Saoud Y., 2013). Evaporation is shown in Figures 1–3 based on the indicator of temperature changes $N_{P_{tos}} \cdot \lg ND = f(\lg t)$, $\lg NG = f(\lg t)$, $\lg N_{P_{tos}} = f(\lg t)$ a graph is generated based on the equation data. The values of optical density, evaporability, and temperature changes as the test time interval increases are analyzed according to the dependencies (Sangram J., Patil D., and Shrotri A., 2014).

Figure 1 shows the dependence of the decimal logarithm of the thermal energy absorbed by the oxidation products on the decimal logarithm of the time and temperature of the test oils under study. $\lg ND = f(\lg t)$.

**Figure 1. Temperature dependence
on oxidation at test temperatures for
mineral and semi-synthetic oils:**

- 1 – MS –20 (180 °C);
- 2 – MS –20 (170 °C);
- 3 – MS –20 (160 °C);
- 4 – AeroShell Oil W l5W-50 (180 °C);
- 5 – AeroShell Oil W 15W-50 (170 °C);
- 6 – AeroShell Oil W 15W-50 (160 °C);
- 7 – MS-8P (180 °C);
- 8 – MS –8P (170 °C);
- 9 – MS –8P (160 °C)

The dependencies are described by linear equations for the studied temperatures:

For MS-20 oil:

$$160\text{ °C } gN_D = 2,22\text{ } lgt - 0,379 \quad (1)$$

$$170\text{ °C } lgN_D = 2,41\text{ } lgt - 0,286 \quad (2)$$

$$180\text{ °C } lgN_D = 2,767\text{ } lgt - 0,422 \quad (3)$$

The coefficient of determination is
(160 °C) = 0,995; (170 °C) = 0,992; (180 °C) = 0,997.

AeroShell Oil W15 for W-50 oil:

$$160\text{ °C } lgN_D = 2,734\text{ } lgt - 1,705 \quad (4)$$

$$170\text{ °C } lgN_D = 2,726\text{ } lgt - 1,354 \quad (5)$$

$$180\text{ °C } lgN_D = 3,05\text{ } lgt - 1,401 \quad (6)$$

Coefficient of determination (160 °C) = 0.995; (170 °C) = 0.996; (180 °C) = 0.992.

For MS-8P oil:

$$160\text{ °C } lgN_D = 2,269\text{ } lgt - 1,037 \quad (7)$$

$$170\text{ °C } lgN_D = 2,671\text{ } lgt - 1,196 \quad (8)$$

$$180\text{ °C } lgN_D = 3,189\text{ } lgt - 1,593 \quad (9)$$

Coefficient of determination (160 °C) = 0.992; (170 °C) = 0.998; (180 °C) = 0.998.

The calculation of the decimal logarithm analysis of the thermal energy absorbed by oxidation products for MS-20 oil at a test temperature of 170 °C is performed as follows: the $lgND$ dependence for five values obtained from the oil test at 170 °C over the same time interval (8, 16, 24, 32, 40 hours) is as follows:

$$170\text{ °C } lgND = 2,293\text{ } lgt - 1,149 \quad (10)$$

can determine $lgND$ values for subsequent test hours, e.g. 48 hours

$$lgND = 2,293 \cdot 1,681 - 1,149 = 3.705 \quad (11)$$

Comparing the calculated values of $lgND$ = 3.705 with the experimental value of $lgND$ = 3.777, it was found that the relative error of the calculated value from the experiment is 1.9%.

Calculations were performed for all oils according to test values from three to ten for the decimal logarithm $lgND$ absorbed by ox-

idation products of thermal energy (Singh G., Wani M. F., and Wani M. M., 2021).

The approximate results of the experimental and computational methods for determining the $lgND$ indicator, with a relative error of no more than 6%, are presented in Formula 1.

Thus, to analyze the indicators of heat energy absorbed by oxidation products, it is sufficient to conduct five experiments, the duration of which is 40 hours (Dautrebande O. and Desreumaux B., 2003).

Figure 2 shows the dependence of the decimal logarithm of the thermal energy absorbed by the evaporation products on the decimal logarithm of the testing time and temperature of the studied oils. $lgNG = f(lgt)$

The dependencies are expressed by linear equations of the studied temperatures:

For MS-20 oil:

$$160\text{ °C } lgNG = 2,018\text{ } lgt + 0,705 \quad (12)$$

$$170\text{ °C } lgNG = 1,768\text{ } lgt + 1,137 \quad (13)$$

$$180\text{ °C } lgNG = 1,386\text{ } lgt + 2,009 \quad (14)$$

The coefficient of determination is
(160 °C) = 0.994; (170 °C) = 0.994; (180 °C) = 0.999.

For AeroShell Oil W15W-50 oil:

$$160\text{ °C } lgNG = 1,694\text{ } lgt + 1,405 \quad (15)$$

$$170\text{ °C } lgNG = 1,872\text{ } lgt + 1,184 \quad (16)$$

$$180\text{ °C } lgNG = 1,804\text{ } lgt + 1,484 \quad (17)$$

The coefficient of determination is
(160 °C) = 0.997; (170 °C) = 0.998; (180 °C) = 0.999.

For MS-8P oil:

$$160\text{ °C } lgNG = 1,726\text{ } lgt + 2,726 \quad (18)$$

$$170\text{ °C } lgNG = 1,712\text{ } lgt + 2,901 \quad (19)$$

$$180\text{ °C } lgNG = 2,132\text{ } lgt + 2,456 \quad (20)$$

The coefficient of determination is
(160 °C) = 0.999; (170 °C) = 0.999; (180 °C) = 0.991.

**Figure 2. Time dependence of thermal
energy absorbed by evaporation
products at test temperatures for
mineral and semi-synthetic oils:**

- 1 – MS-20 (180 °C);
- 2 – MS-20 (170 °C);
- 3 – MS-20 (160 °C);
- 4 – AeroShell Oil W l5W-50 (180 °C);
- 5 – AeroShell Oil W 15W-50 (170 °C);
- 6 – AeroShell Oil W 15W-50 (160 °C);
- 7 – MS-8P (180 °C);
- 8 – MS-8P (170 °C);
- 9 – MS-8P (160 °C)

Aero-Shell Oil W 15W-50 oil at a temperature of 160 °C according to five values obtained at the same time intervals (8, 16, 24, 32, 40) $lgNz=f(lgt)$ the relationship has the following linear form:

$$160\text{ °C } lgNG = 1,555\ lgt + 1,582 \quad (21)$$

$lgNG$ value can be determined for subsequent test hours, e.g. 48 hours:

$$lgNG = 1,555 \cdot 1,582 + 1,582 = 4,195 \quad (22)$$

Calculated $lgNG(hisob) = 4,195$ value obtained experimentally $lgNG(tajriba) = 4,252$ value, it was determined that the relative error of the calculated value from the experiment is 1.3%.

Similarly, calculations were performed for the decimal logarithm of the thermal energy absorbed by the evaporation products using test values from three to ten. The results of the verification of the compatibility of the experimental and calculation methods are presented in Table 1, which show that the error does not exceed 4%.

Thus, to analyze the indicators of thermal energy absorbed by evaporation products,

five experiments are sufficient, the duration of which is 40 hours.

The dependencies are described by linear equations for the studied temperatures.

For MS-20 oil:

$$160\text{ °C } lgNPtos = 2,304\ lgt - 0,517 \quad (23)$$

$$170\text{ °C } lgNPtos = 2,384\ lgt - 0,241 \quad (24)$$

$$180\text{ °C } lgNPtos = 2,687\ lgt - 0,303 \quad (25)$$

The coefficients of determination are respectively (160 °C) = 0.996; (170 °C) = 0.991; (180 °C) = 0.995.

For AeroShell Oil W 15W-50 oil:

$$160\text{ °C } lgNPtos = 2,833\ lgt - 1,89 \quad (26)$$

$$170\text{ °C } lgNPtos = 2,923\ lgt - 1,706 \quad (27)$$

$$180\text{ °C } lgNPtos = 3,085\ lgt - 1,46 \quad (28)$$

The coefficients of determination are respectively (160 °C) = 0.996; (170 °C) = 0.992; (180 °C) = 0.995.

For MS-8P oil:

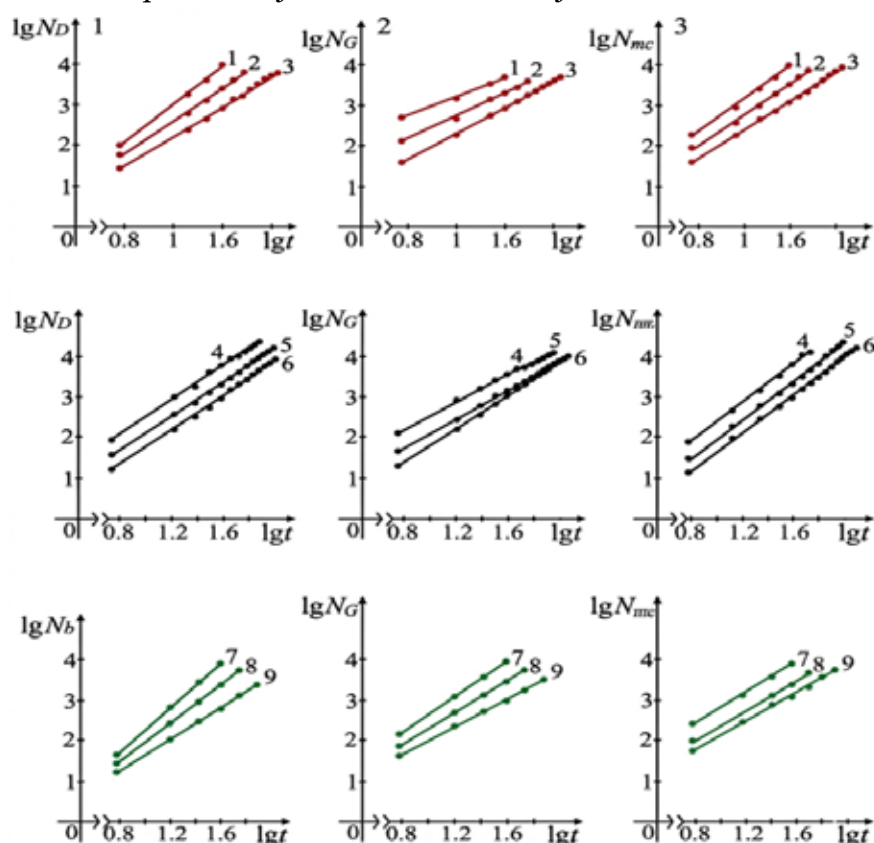
$$160\text{ °C } lgNPtos = 2,221\ lgt - 0,307 \quad (29)$$

$$170\text{ °C } lgNPtos = 2,196\ lgt - 0,089 \quad (30)$$

$$180\text{ °C } lgNPtos = 2,342\ lgt - 0,233 \quad (31)$$

The coefficients of determination are respectively (160 °C) = 0.991; (170 °C) = 0.985; (180 °C) = 0.994.

Figure 3. Shows the dependence of the decimal logarithm of the temperature change indicator on the decimal logarithm of the test time and temperature of the studied aviation fuel oils. $lgNPtos=f(lgt)$



Dependence of the decimal logarithm of the temperature change indicator on the decimal logarithm of time under the conditions of testing mineral and semi-synthetic oils:

1 – MS-20 (180 °C); 2 – MS-20 (170 °C); 3 – MS-20 (160 °C); 4 – AeroShell Oil W 15W-50 (180 °C); 5 – AeroShell Oil W 15W-50 (170 °C); 6 – AeroShell Oil W 15W-50 (160 °C); 7 – MS-8P (180 °C); 8 – MS-8P (170 °C); 9 – MS-8P (160 °C)

Decimal logarithm of the temperature change indicator of MS-8P oil at a test temperature of 160 °C $lgNP_{tos}$ by five values (8, 16, 24, 32, 40) obtained as a result of oil testing at 160 °C $lgNP_{tos} f(lgt)$ the relationship has the following linear form:

$$lgNP_{tos} 2,089 \cdot lgt - 0,153 \quad (32)$$

$lgNP_{tos}$ in the next test hours, e.g. 48 hours:

$$lgNP_{tos} 2,089 \cdot 1,681 - 0,153 = 3,258 \quad (33)$$

Calculated $lgN_{ptos}^{(hisob)} = 3,358$ value obtained experimentally $lgN_{ptos}^{(tajriba)} = 3,405$ compared to the value, the difference between the calculated value and the experimental value with a relative error is 1.39%.

Similarly, calculations were performed using test values from three to ten for the decimal logarithm of the temperature change indicator. lgN_{ptos}

The results of the verification of the convergence of experimental and calculation methods are presented in Table 1, which show that the relative error does not exceed 5%.

Thus, five experiments with a duration of 40 hours are sufficient to analyze the indicators of temperature changes.

The results of the convergence of experimental and calculation data for mineral and semi-synthetic oils are presented in Table 1.

Table 1. Results of the correspondence between experimental and calculated data

Number of points	MS-20			AeroShell Oil W 15W-50			MS-8P		
	160 °C	170 °C	180 °C	160 °C	170 °C	180	160 °C	170 °C	180 °C
<i>lgND, Density %</i>									
Point 1	3,767	4,553	1,444	5,142	3,415	1,965	3,127	1,608	1,279
Point 2	3,624	2,650	0,697	4250	3.195	1,085	2,682	0,777	–
Point 3	2,622	1,440	–	4,133	2,359	0,513	1,104	–	–
Point 4	1,325	0,857	–	4,062	2,184	0,486	–	–	–
Point 5	1,181	–	–	3,753	2,178	–	–	–	–
Point 6	1,104	–	–	2,857	2119	–	–	–	–
Point 7	0,864	–	–	2,591	1,804	–	–	–	–
Point 8	0,458	–	–	2,067	1,263	–	–	–	–
<i>lgNG, Evaporability %</i>									
Point 1	1,453	1,233	0,379	4722	3267	0,206	0,252	0,215	0,852
Point 2	1290	0,778	0,092	2,689	1,309	0,185	0,206	0,018	–
Point 3	1,230	0,185	–	1733	0,633	0,028	0,189	–	–
Point 4	1,204	0,153	–	1,382	0,309	0,006	0,024	–	–
Point 5	0,933	–	–	1,097	0,112	–	–	–	–
Point 6	0,655	–	–	0,829	0,054	–	–	–	–
Point 7	0,578	–	–	0,686	0,054	–	–	–	–
Point 8	0,525	–	–	0,530	0,007	–	–	–	–
<i>lgNP_{tos}, Temperature variability %</i>									
Point 1	1,864	4,611	1,888	4,383	5,065	2,862	1,798	3,403	2,242
Point 2	1,748	2,730	0,849	4,246	3,705	2,679	1,176	2,316	–

Number of points	MS-20			AeroShell Oil W 15W-50			MS-8P		
	160 °C	170 °C	180 °C	160 °C	170 °C	180	160 °C	170 °C	180 °C
Point 3	1,739	1,498	-	3,667	3437	1,581	0,868	–	–
Point 4	1,597	0,876	-	3,455	3,074	0,489	0,162	–	–
Point 5	1,509	-	-	2,341	3,064	-	–	–	–
Point 6	1,289	-	-	2,185	2,446	-	–	–	–
Point 7	0,952	-	-	1,681	1719	-	–	–	–
Point 8	0,840	-	-	1,423	1,173	-	–	–	–

Casting stability of mineral and semi-synthetic oils depending on temperature and testing time. Thus, as seen from the table above, the oil samples taken for the study were tested at three temperature ranges and by three parameters (density, viscosity, changes under the influence of temperature). As seen from the test results, as a result of operating the unit under load, all three oil parameters change, which in turn has a serious negative impact on the friction parts of this unit; the oils cannot perform

the functions of lubrication and cooling of the unit parts, and it should be noted that as the temperature increases, the indicators change in a negative direction. Based on the above, we conclude that the loads during the operation of the unit are directly proportional to the composition and quality of the oil, i.e., by reducing the load while maintaining the quality of the oil and increasing the operating time of its parts, it is possible to increase the intervals of repair work in the units.

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submitted 04.05.2026;

accepted for publication 18.05.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-107-114



INVERSE PIEZOELECTRIC EFFECT AS A FOUNDATION FOR INNOVATIVE APPLICATIONS

(Application of specialized composite materials in the
further development of innovative applications based on
the inverse piezoelectric effect, including applications
for intelligent automotive transportation systems)

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Cite: Baranovskyi H. (2026). *Inverse Piezoelectric Effect as a Foundation for Innovative Applications. (Application of specialized composite materials in the further development of innovative applications based on the inverse piezoelectric effect, including applications for intelligent automotive transportation systems). Austrian Journal of Technical and Natural Sciences 2026, No 5–6.* <https://doi.org/10.29013/AJT-26-5.6-107-114>

Abstract

This article examines the application of the inverse piezoelectric effect as a fundamental physical principle for the development of innovative engineering applications in precision mechanics, automation systems, and advanced electromechanical devices. Particular attention is devoted to the design and development of piezoelectric motors intended for high-precision positioning systems, miniature actuators, and next-generation lighting and intelligent transportation technologies.

The publication analyzes the engineering principles of piezoelectric motors operating on the basis of the inverse piezoelectric effect and considers their advantages in achieving high positioning accuracy, compact dimensions, low weight, and enhanced operational reliability. The study further examines the influence of structural design solutions on the functional characteristics of precision stepper motors and other miniature electromechanical systems.

Special emphasis is placed on the application of advanced composite materials as structural elements of piezoelectric motors. The article discusses the contribution of specialized composite materials to reducing the weight and dimensions of electromechanical devices while improving their mechanical strength, durability, dynamic characteristics, and manufacturing flexibility.

The publication further examines prospective directions for the development of innovative applications based on the inverse piezoelectric effect, including intelligent automation systems, precision mechanical equipment, miniaturized electromechanical devices, advanced lighting technologies, and intelligent automotive transportation systems. The study concludes that the integration of inverse piezoelectric technologies with modern composite materials represents a promising direction for the development of next-generation precision engineering products and high-performance electromechanical systems.

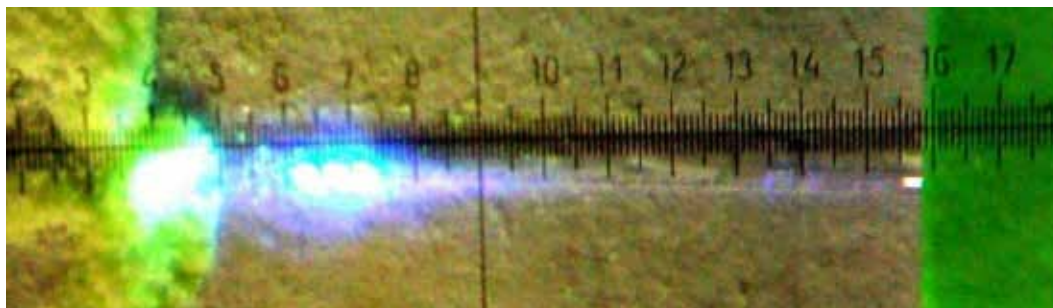
Keywords: *Inverse piezoelectric effect; piezoelectric motor; composite material; piezoelectric motor rotor*

Introduction

The continued development of innovative applications based on the inverse piezoelectric effect represents one of the most

promising directions in modern precision engineering, automation, and intelligent electromechanical systems.

Figure 1.



Experimental investigations of piezoelectric motors operating on the basis of the inverse piezoelectric effect, together with attempts to employ them as precision stepper motors, have revealed the need to address a number of important engineering challenges. Many of these challenges arise from the incompatibility between the capabilities of modern control processors and their advanced software functions and the structural limitations of existing piezoelectric motor designs, which were originally developed using conventional engineering materials. Although these materials performed satisfactorily within previous generations of electronic components and control systems, they no longer fully satisfy the performance requirements

imposed by contemporary high-precision electromechanical applications.

These circumstances create a need for the development of new structural concepts based on advanced composite materials capable of improving the mechanical, dynamic, and operational characteristics of piezoelectric motors while ensuring compatibility with modern digital control technologies. Such an approach provides opportunities for reducing weight and overall dimensions, increasing positioning accuracy, improving operational reliability, and expanding the practical application of inverse piezoelectric technologies in intelligent automation systems, precision engineering, and smart transportation.

Figure 2.



Figure 3.

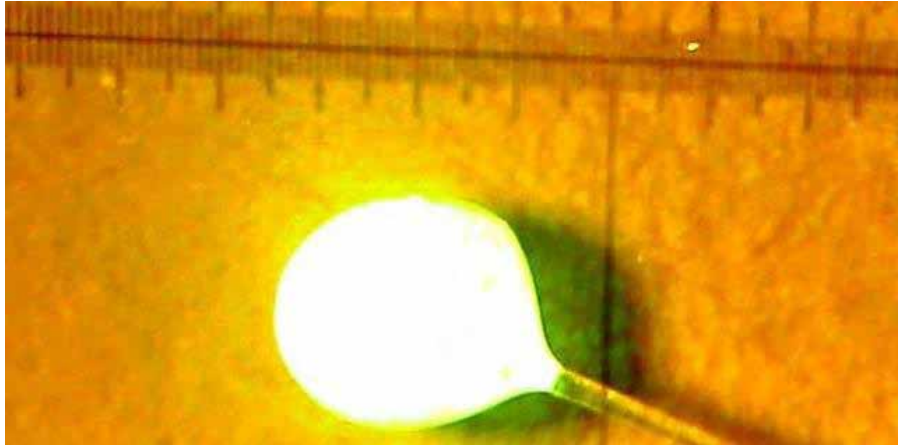


Figure 4.

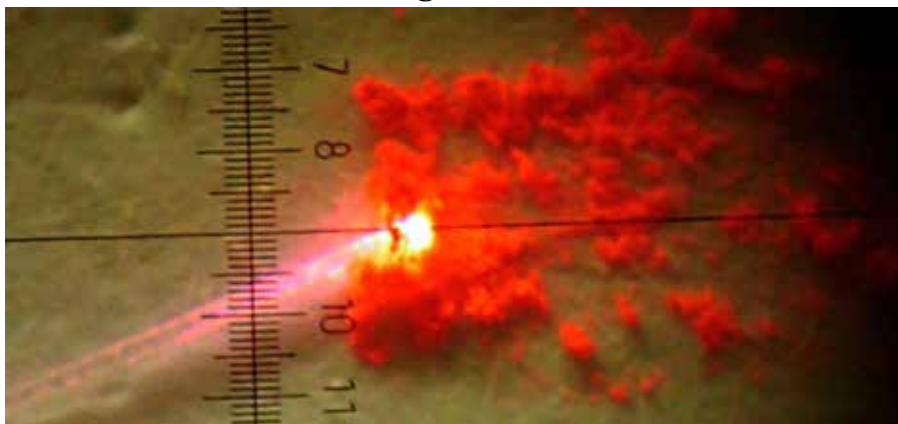
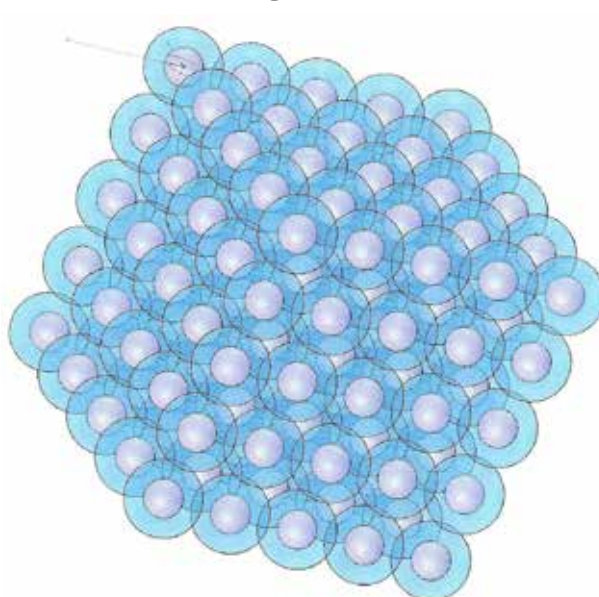


Figure 5.



Figure 6.



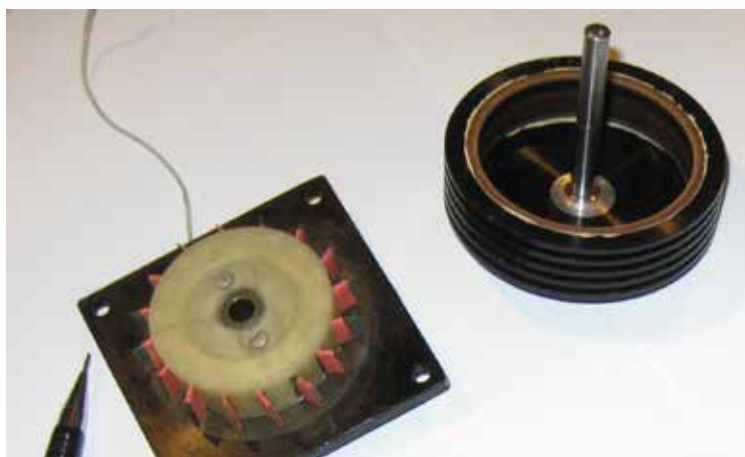
As can be seen from the photograph of one type of piezoelectric motor, its construction incorporates conventional engineering materials, including anodized aluminum, bronze, stainless steel, laminated plastics, and similar structural materials.

Testing of these types of piezoelectric motors, together with attempts to employ them as precision stepper motors, has revealed the need to address a number of important engineering challenges. Many of these challenges arise from the incompatibility between the capabilities of modern control processors and their advanced software functions and the structural limitations resulting from the use of traditional engineering materials, which performed

satisfactorily with previous generations of electronic components but no longer fully meet the requirements of modern digital control systems.

Furthermore, the programmable control and drive management system, particularly when the motor operates in stepper motor mode, has highlighted the critical need to ensure that the mechanical properties of these structural materials are fully compatible with the stability requirements governing their response to piezoelectric excitation pulses. This compatibility is essential for achieving the positioning accuracy, dynamic stability, repeatability, and operational reliability required of modern high-precision piezoelectric drive systems.

Figure 7.



The positioning accuracy required of stepper versions of piezoelectric motors, combined with programmable control provided by modern monitoring and control systems, necessitated stable coordination between the output characteristics of the motor and the parameters of the electrical pulse signals applied to the piezoceramic ring.

Analysis of the kinematic transmission chain extending from the plain bearing to the piezoceramic ring, from the spring-steel elastic elements soldered to the piezoceramic ring to the friction ring, and subsequently from the friction ring to the motor rotor, demonstrated that the principal cause of the wide variation in the motor's output characteristics is the limited responsiveness of the elements comprising this transmission chain to changes and even short-term fluctuations in the control and feedback pulse signals.

Analytical investigations further demonstrated that the principal limitation of the system lies in the absence of an effective mechanism for the nearly instantaneous distribution or dissipation of the excitation pulses applied to the piezoelectric ring.

As an initial step in the optimization process, it was decided to replace the conventional piezoelectric ceramic used in the piezoelectric ring with a composite piezoceramic material containing specially selected components that are substantially insensitive to the excitation pulses applied to the piezoelectric ring.

Previous experimental investigations indicated that such performance may be achieved through the uniform incorporation of synthetic diamond microspheres into a specially formulated piezoceramic matrix.

Figure 8.



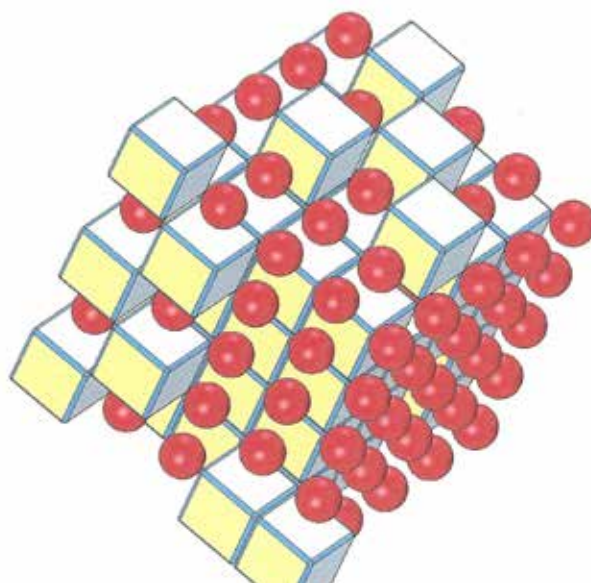
A model of such a material illustrates its three-dimensional structure, consisting of a large number of spherical capsules arranged in at least two structural levels.

The first structural level consists of microspheres manufactured from synthetic diamonds. Modern production technologies make it possible to manufacture these microspheres with extremely high dimension-

al accuracy, minimal production costs, and a comparatively low cost of the raw material itself.

Furthermore, the requirements imposed on synthetic diamonds for this application do not include the stringent specifications for optical transparency or crystal purity that are characteristic of gemstones intended for jewelry applications.

Figure 9.



The following photograph illustrates the structure of the proposed composite material.

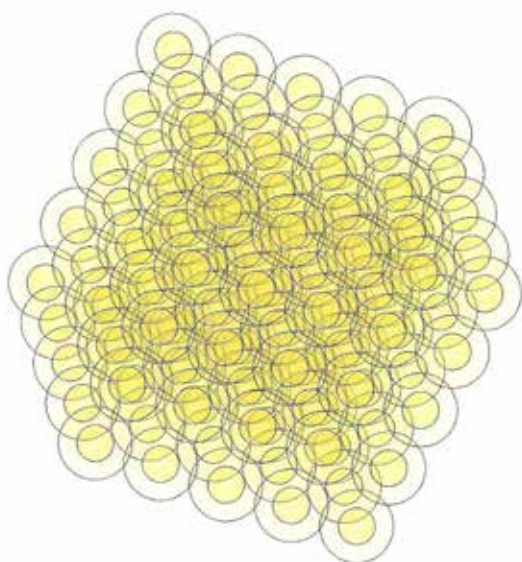
Following the fabrication of the synthetic diamond microspheres, they are coated

with a moist ceramic composition and subsequently placed into a molding die. During the pressing process, the ceramic material surrounding the diamond microspheres

undergoes volumetric deformation, forming a large number of cubic microstructures, each containing a synthetic diamond microsphere located at its geometric center.

The resulting structure may be described as pseudo-porous, since the synthetic diamond microspheres, being practically insensitive to the excitation pulses, promote the nearly uniform distribution of electrical signals or excitation pulses throughout the surrounding ceramic microcubes. This structural configuration provides exceptionally high stability and homogeneity of signal propagation within the pseudo-porous piezoceramic ring, thereby improving the dynamic response and operational stability of the piezoelectric motor.

Figure 10.

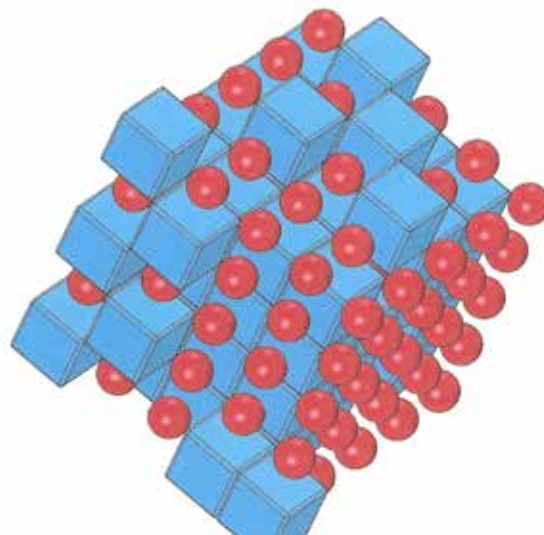


It should also be noted that, because spring-steel elastic elements are soldered to the outer cylindrical surface of the piezoelectric ring, the uniform distribution of the excitation pulse throughout the piezoelectric ring makes it possible to satisfy the principal requirements for the stability and homogeneity of the driving vibration pulses transmitted from these elastic elements to the rotor in frictional contact with them.

As a result, the force impulses acting on the rotor become more uniform in both magnitude and temporal distribution, thereby improving the positioning accuracy, repeatability, dynamic stability, and operational

reliability of the piezoelectric motor, particularly when operating in precision stepper motor mode under digital control.

Figure 11.



It is now appropriate to return to the issue of rotor wear resistance.

Considering that the ends of the spring-steel elastic elements remain in continuous dynamic contact with the inner surface of the rotor, and assuming that the excitation pulses are distributed non-uniformly throughout the three-dimensional structure of a rotor manufactured from conventional engineering ceramic, it can be assumed that the force transmitted from the ends of the spring elements to the rotor surface is likewise non-uniform. Such non-uniform loading results in uneven wear of the rotor's inner surface and, consequently, in radial runout of the motor output shaft.

If the conventional piezoelectric ring material is replaced with the proposed pseudo-porous composite piezoceramic, the dependence of rotor wear on the non-uniform distribution of excitation pulses within the ceramic material is expected to decrease significantly. This improvement should have a positive influence on the output characteristics and operational performance of the piezoelectric motor.

The principal performance parameters expected to benefit from this modification include:

- reduction of radial runout of the motor shaft;

- improved synchronization of all mechanical interfaces between the structural components of the motor;
- increased service life of the motor;
- simplified simultaneous synchronization of the operating characteristics of multiple motors used in systems converting rotary motion into the linear displacement of machine tool carriages or positioning stages;
- improved uniformity and stability of the rotor rotational speed.

It should also be noted that, in the existing motor configuration, the vibration characteristics of the entire electromechanical system are directly influenced by the non-uniform and cyclic transmission of mechanical forces from the special ceramic material to the rotor and, ultimately, to the motor output shaft.

System-level analysis and computer modeling have further demonstrated that replacing the conventional rotor material with a composite material analogous to the pseudo-porous structure proposed for the piezoceramic ring may also provide significant advantages.

In this case, the structural architecture of the composite material remains unchanged, while only the constituent materials are modified.

For example, to improve the durability of the structural components of the motor, the core material may be changed from synthetic diamond to beryllium, while the surrounding matrix is formed from aluminum.

Aluminum possesses sufficient ductility to ensure the required cold-flow characteristics during volumetric plastic calibration of the geometric configuration of the motor elements and structural components.

Numerous combinations of core and matrix materials may be selected for the composite capsules, thereby providing maximum flexibility in the design of control and monitoring systems employing piezoelectric motor drives.

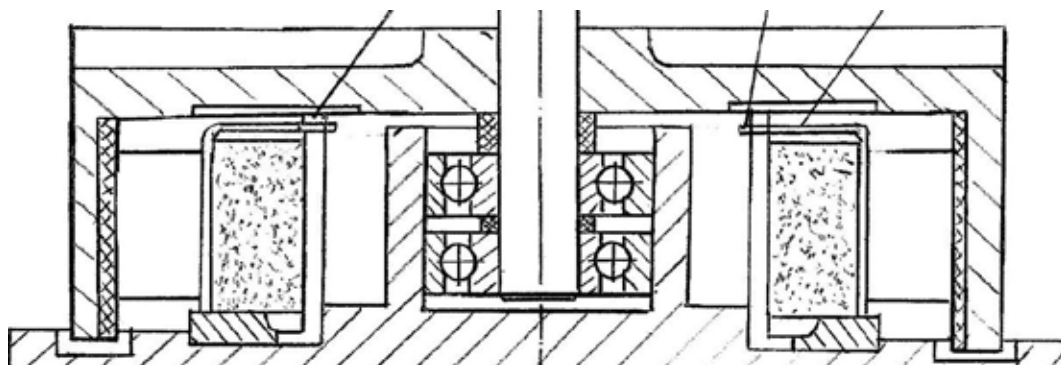
It is also appropriate to address the design of the spring-steel elastic elements.

When these elements are attached to the piezoceramic ring by soldering, an additional group of engineering problems arises, primarily associated with the inability to achieve the required levels of dimensional accuracy, mechanical strength, and long-term durability. These limitations are well known and result from the inherent characteristics of conventional soldering materials.

Particularly complex are the technological issues associated with preparing the outer surface of the piezoceramic ring for soldering and with applying a metallic or equivalent intermediate layer capable of providing a reliable soldered joint between the ring and the spring-steel elastic elements.

The author of the present publication proposes solving this problem by eliminating soldered joints entirely and replacing them with an optimized spring-element assembly manufactured as a continuous spring band incorporating the required elastic fingers.

Figure 12.



This spring band is mechanically clamped around the outer diameter of the piezoceramic ring, providing several additional advantages for optimizing the performance of the piezoelectric motor, including:

- uniform circumferential distribution of the spring elements around the piezoceramic ring;

- the ability to adjust the clamping force between the spring band and the outer surface of the piezoceramic ring;
- simple, rapid, and reliable replacement of the spring band in the event of wear of the elastic fingers;
- substantial reduction in manufacturing cost while simultaneously improving the efficiency, reliability, and overall quality of the piezoelectric motor.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-115-120



ROBOTIC SYSTEMS FOR FIBER-OPTIC CABLE INSTALLATION: IMPLEMENTATION EXPERIENCE

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Cite: Bekirov R. (2026). *Robotic Systems For Fiber-Optic Cable Installation: Implementation Experience*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-115-120>

Abstract

The article discusses the pressing issue of automating the process of constructing and upgrading telecommunications infrastructure, particularly in relation to the implementation of robotic systems for installing fiber-optic communication lines. With the exponential increase in data consumption, there is a need for large-scale expansion of access networks, especially within the context of smart city initiatives and 5G/6G standards. Traditional excavation and installation techniques face significant time, cost, and security challenges. The technical details and principles of operation of autonomous earthmoving complexes, robotic cable operators that can penetrate existing sewer systems, and specialized unmanned aerial vehicles that install overhead lines are also considered. Special attention is paid to the practical aspects of implementing these technologies, including assessing economic efficiency, minimizing negative impacts on the urban environment, and reducing the risk of damage to existing underground infrastructure. Based on the analysis of case studies, key obstacles to the widespread adoption of these technologies have been identified, such as the high initial cost of equipment, the need to adapt regulations, and the lack of qualified personnel to service robotic systems. It is concluded that the transition to automated cabling is an inevitable step in the development of telecommunications construction, requiring the development of industry standards, a review of the regulatory framework, and specialized training programs for operators.

Keywords: *robotic systems, laying of overhead cables, fiber-optic communication lines, automation of telecommunications, micro-trench laying, trenchless technologies, robot cable operators, autonomous earthmoving complexes, implementation experience, communication infrastructure, fiber-optic networks, digitalization of construction*

Relevance of the study

The relevance of this study is due to the rapid growth of global data traffic and the need for large-scale deployment of broadband access networks, especially within the context of smart city initiatives and the de-

velopment of fifth- and sixth-generation mobile communication standards.

Traditional methods of laying fiber-optic communication lines, such as the open trench method and classical aerial installation, are facing serious limitations. These include the

high cost of excavation, lengthy approval processes, significant disruption to urban infrastructure, and a critical shortage of skilled workers. In modern conditions, automation and robotization of construction processes have become not only a tool for optimizing operational activities, but also an urgent necessity for the rapid development of the telecommunications industry. The introduction of robotic systems makes it possible to significantly increase the speed and accuracy of work, minimize the risks of damage to existing underground utilities, and ensure the highest level of occupational safety (Lalam N. et al., 2022).

Despite the obvious technological benefits, several technological, economic, and regulatory obstacles have hindered the widespread adoption of these innovations. Therefore, a thorough analysis of practical experiences with their implementation is crucial for addressing these issues and making progress.

The purpose of the study

The purpose of this study is to comprehensively analyze the current state and practical experience of using robotic systems for laying fiber-optic communication lines, as well as to evaluate the possibilities of their integration into standard telecommunication construction processes.

To achieve this goal, several interrelated tasks are consistently considered in the work. In particular, a detailed analysis of the technical characteristics of autonomous earthmoving machines, trenchless robots, and specialized drones designed for the installation of overhead lines is carried out. In addition, the real economic efficiency and operational advantages of using robotics in comparison with traditional methods are evaluated. The key barriers preventing the scaling of these solutions are also identified.

As a result of the research, practical recommendations have been developed that will help optimize the implementation of robotic complexes, adapt estimated standards, and form new industry standards. These recommendations will help accelerate and reduce the cost of digitalization of the communications infrastructure.

Materials and research methods

Leading manufacturers of special equipment base the research on an extensive database that includes technical specifications and operational documentation of modern robotic cable-laying systems presented on the market. Statistical reports and the results of the implementation of pilot and commercial projects to automate the construction of fiber-optic communication lines in various climatic and urban conditions were also studied.

In addition, current regulatory legal acts, building codes, and regulations governing excavation and installation of telecommunications networks, as well as analytical reviews from the world's leading telecommunications agencies, were used.

The methodological basis of the research was the system analysis and synthesis of scientific and technical information, which allowed us to streamline knowledge about modern robotic solutions. To assess the effectiveness of the implementation, a comparative analysis method was used, in which the technical and economic indicators of traditional and robotic methods for laying fiber-optic communication lines were compared.

The results of the study

In the modern world of telecommunications construction, there is a rapid transition from traditional mechanized methods to fully autonomous and robotic technologies. This is due to the increasing density of urban development and the growing demands on environmental safety.

One of the most promising and actively implemented areas is the robotic micro-trenching gasket. Within the framework of this technology, autonomous milling complexes equipped with satellite navigation systems (GNSS) and integrated ground-penetrating radars are used. These robots can independently form narrow trenches up to 30 centimeters deep, while simultaneously laying micro cables and sealing them with polymer compounds (Dong X., 2025).

Practical examples of the use of such systems in megacities show that the use of autonomous micro-transmitters avoids the need for large-scale excavation of the road surface, which, in turn, contributes to the preservation of road infrastructure and re-

ducing social tension (Vdovichenko O., Perepelitsyn A., 2021). In the field of trenchless technologies, revolutionary changes have been achieved through the automation of horizontal directional drilling (HDD) installations.

Modern robotic complexes for horizontal directional drilling are equipped with automatic rod feeding and connection systems,

as well as algorithms that analyze inclinometer data in real time for predictive control of the drilling trajectory. This allows the robot to independently adjust the angle of inclination and avoid collisions with existing underground utilities, the maps of which are uploaded to its on-board computer thanks to information modeling (BIM) technologies (Table 1).

Table 1. *Modern robotic directional drilling systems*
(Khorov E. et al., 2018; Lin T. H. et al., 2026)

The model of the complex	Traction/reverse force, tf	Max. puncture length, m	Automation level	Key features and applications
Grundodrill 4X	40	up to 300	Semi-automatic (automatic rod feeding, automatic trajectory monitoring)	Compact urban complex; ideal for laying cable sewers and cable duct covers in cramped building conditions; low vibration level
JT20/24 Navigator	9.5	up to 200	Automated (AutoThrust system, intelligent drilling head control)	Lightweight class for urban access networks; built-in DigiTrak Falcon F5 locator with feedback; minimal work area
D24×40 S3 Navigator	11.3	up to 250	Robotic (automatic rod loading, CECE system)	Intelligent rod load control system; optimization of drilling fluid flow; high productivity on medium-sized projects
XZ360E	36	up to 450	Semi-automatic (electric drive, automatic angle monitoring system)	Fully electric drive with zero emissions – optimal for environmentally sensitive areas and enclosed areas; low noise level
AVN-200/250	200–250	up to 500	Fully automated (microtunnel shield with remote control)	Microtunneling with clay or rock; continuous laying of reinforced concrete or steel castings for main overhead lines; positioning accuracy ±20 mm
UNB-600 “Vityaz”	60	up to 350	Semi-automatic (automated rod feeding system, digital inclinometer)	Domestic development for medium and mainline crossings; adaptation to frozen and rocky soils; high maintainability
Goodeng DR30–200	30	up to 300	Robotic (automatic rod manipulator, telemetry system)	Low-cost solution for telecom operators; high speed of installation/disassembly; integration with mobile applications for process monitoring

Introsopic cable robots, designed for laying fiber-optic cables in existing underground

utilities, deserve special attention (Zhao W. et al., 2021). These devices are compact tracked

or wheeled platforms equipped with manipulators, machine vision systems, and lidars. They are capable of performing pre-cleaning of collectors, performing flaw detection of their walls, and pushing through the cable, adapting the traction force depending on the coefficient of friction (Fig. 1).

Figure 1. *Mobile tele-inspection robotic system*



Heavy cargo unmanned aerial vehicles (UAVs) are successfully used in difficult, mountainous, and swampy areas, as well as when overcoming wide water barriers. These drones are capable of not only winding the pilot cable but also mounting self-supporting optical cables (ACS) directly onto the supports, using computer vision to precisely position the fasteners. Statistical data collected during pilot and commercial projects on the robotization of fiber-optic cable construction from 2023 to 2025 demonstrate the high efficiency of these technologies (Corrêa M. F.S. et al., 2026).

Analysis of production indicators shows that using autonomous microtransmission systems increases cable laying speed from 50–80 m per shift to 300–500 m per shift in urban environments, providing a 4–6 fold increase in labor productivity. The cost of subsequent asphalt or tile restoration is reduced by 60–75% due to the minimum opening area.

Statistics show that using HDD reduces the risk of damage to existing underground utilities by 85% compared to manual control.

In addition, reducing the number of maintenance crews from 4–5 to 1–2 operators makes it possible to reduce the wage fund at a particular facility by 40%.

The use of introspective robots in the process of working in existing sewer systems has significantly increased the average span length between wells. Without the use of additional winches, this figure increased by 300%. In addition, the number of incidents related to optical fiber breakage or critical bending decreased by 92%.

The use of heavy unmanned aerial vehicles (UAVs) during the construction of overhead lines in difficult geographical conditions significantly reduced the time required for the construction of transitional spans through rivers and ravines by 5–7 times. At the same time, the risks of high-altitude injuries are completely eliminated, which traditionally account for up to 15% of the total number of accidents during linear construction. According to aggregate macroeconomic indicators, the global market of robotic equipment for telecommunications construction demonstrates a stable average annual growth rate (CAGR) of 16–18% (Moody D., 2022).

Economic modeling demonstrates that, despite significant initial capital expenditures (CAPEX) for the acquisition of robotic complexes, their payback period during intensive operation ranges from 18 to 30 months. The integration of robotics with digital counterparts of communication facilities makes it possible to reduce the overall design and construction time of access networks by 35–40%. In addition, the general industrial injury rate (LTIFR) at facilities where autonomous systems are used is reduced by 95%. This proves not only the economic, but also the high social feasibility of a mass transition to robotic methods of laying fiber-optic communication lines.

The author believes that, despite the high efficiency and strategic importance of robotic systems for laying fiber-optic communication lines, their mass implementation faces a number of systemic problems. Industry monitoring and statistical analysis data confirm these problems.

At the technical and technological level, the main obstacle is the high degree of uncertainty of the real urban and natural envi-

ronment. Analysis of telemetry collected from autonomous micro-transmission complexes and trenchless robots from 2023 to 2025 shows that in dense urban areas, the so-called “urban canyons,” critical failures in satellite navigation systems (GNSS) occur on average in 35–40% of cases. This forces switching to manual or semi-automatic control and reduces the claimed productivity by 25–30%.

In addition, machine vision and laser scanning systems are highly sensitive to adverse weather conditions. The statistics of industrial incidents show that during periods of heavy precipitation, dust storms, or thick fog, the probability of false alarms of emergency stop systems increases by 45–60%, which leads to unplanned downtime of equipment (Wang L. et al., 2024). Difficult geological conditions, such as the presence of boulders or seasonally frozen soils, cause cutting tool failures and emergency stops in about 20% of shifts, increasing the time required for repairs and maintenance.

The economic problems associated with the introduction of robotics are both macro- and micro-financial in nature. They are driven by extremely high initial capital costs and hidden operating costs. Statistical data on purchases of specialized equipment show that the cost of one autonomous robotic complex for laying fiber-optic communication lines is on average four to five times higher than the cost of similar functionality of traditional mechanized equipment. In addition, the operating costs (OPEX) are compounded by the need for expensive maintenance. The annual cost of sensor calibration, software updates, and replacement of specific components ranges from 18% to 22% of the initial cost of the machine (Sang Z., Li K., 2019).

Economic modeling conducted on the database of large telecommunications contractors has revealed a significant discrepancy between projected and actual payback indicators. If business plans set a return on investment (ROI) of 24–30 months, actual data, based on three years of operation, show an increase in this period to 48–54 months. This discrepancy is due to underestimation of indirect costs, such as the need for mobile repair teams with mechatronics engineers and downtime related to waiting for foreign component supply under sanctions and logistical restrictions.

The issue remains the outdated regulatory framework, which not only fails to keep pace with technological developments, but also creates artificial administrative barriers. Analysis of the timing of robotics infrastructure projects shows that up to 40% of total construction time is spent on bureaucratic approvals, rather than physical work.

The current codes of regulations and state standards do not contain specific regulations for the acceptance of work performed by fully autonomous systems, which leads to delays in commissioning for about 15% of successfully implemented pilot projects due to technical issues.

One critical aspect is the issue of legal liability. Statistics on insurance claims in the telecommunications industry show an increase in incidents related to damage to nearby underground utilities caused by robotic horizontal directional drilling machines. In 12–15% of these cases, protracted legal disputes arise because the current legislation does not clearly define the distribution of responsibility between the contractor, operator, and developer of the artificial intelligence algorithms controlling the machine.

Another issue is the lack of up-to-date documentation for existing underground utilities. According to statistics from GPR, surveys and tracking, in old urban areas, between 40% and 50% of existing cables and pipes are not registered on cadastral maps or are registered with an error of several meters.

This makes it difficult for even the most advanced robotic algorithms to navigate through the area. Production reports indicate that despite the use of robotics, there is still an average of one incident every 10–15 kilometers where communications are damaged due to uncharted obstacles. This requires manual drilling and control, completely defeating the idea of fully autonomous construction.

According to the author, these statistically confirmed problems require the development of a comprehensive government strategy that aims to modernize the regulatory framework, support innovative projects, and create unified competence centers simultaneously.

Conclusions

Summing up the research, we can state that the introduction of robotic systems into the process of laying fiber-optic communication lines is not only a promising technological trend, but also an objective necessity and an inevitable direction of evolution for the telecommunications industry as a whole.

According to the author, the experience of integrating autonomous microtransmission complexes, robotic horizontal directional drilling rigs, intrascopic cable carriers, and heavy cargo drones has proven their high operational efficiency. This includes multiple increases in labor productivity, significant reduction of risks related to damage to existing underground and aerial infrastructure, minimization of environmental impact, and almost complete elimination of injuries in dangerous work areas.

However, as the statistical and analytical review conducted by the author has shown, several systemic barriers hinder the massive robotization of access network construction. These include high capital and operating costs, vulnerability of machine vision and navigation algorithms to difficult weather and geological conditions, a lack of up-to-date geospatial data, and a shortage of qualified mechatronics engineers.

The author believes that only the simultaneous solution of these technological, economic, administrative, and personnel challenges, through the development of artificial intelligence and creation of digital counterparts for underground infrastructure, can unlock the full potential of robotic systems. This will ensure the rapid, safe, and economically sustainable deployment of fiber-optic networks as data consumption continues to grow exponentially.

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submitted 02.05.2026;

accepted for publication 16.05.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-121-127



NON-CONTACT MONITORING OF WATER AND MILK QUALITY. (The latest developments in the field of non-contact monitoring of drinking water and cow's milk quality based on the principles of electromagnetic resonance spectroscopy)

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Cite: Bessarabenko K. (2026). *Non-Contact Monitoring of Water and Milk Quality. (The latest developments in the field of non-contact monitoring of drinking water and cow's milk quality based on the principles of electromagnetic resonance spectroscopy).* Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-121-127>

Abstract

The article discusses modern developments in the field of non-contact monitoring of drinking water and cow's milk quality based on resonance control methods and complex digital indicators of the dynamic state of the medium.

The growing need for continuous monitoring of water and milk quality under increasing environmental risks, stricter regulatory requirements, and higher food safety standards is emphasized. Particular attention is given to the limitations of traditional control methods based mainly on electrical conductivity measurements and the need for more comprehensive approaches to liquid parameter analysis.

The article presents technical solutions for real-time monitoring of water and milk quality, including devices for assessing integral quality indicators, somatic cell content, fat concentration, lactose content, gas levels, and indicators of animal diseases. Compact energy-efficient devices designed for stationary use and rapid field analysis are also considered.

The implementation of intelligent non-contact monitoring systems is shown to improve the safety, reliability, and efficiency of water and dairy production, transportation, and processing processes.

Keywords: Water quality; Milk quality; Monitoring; Non-contact monitoring; Developments in the field of non-contact monitoring of drinking water and cow's milk quality based on the principles of electromagnetic resonance spectroscopy; Water quality control methodology; Milk quality control methodology; Water conductivity; Milk conductivity; Technological conditions; Technology compliance assurance factor

Inventions in the field of non-contact monitoring of drinking water and cow's milk quality

The quality of drinking water practically determines the quality of life. In all water quality control methodologies, water conductivity is considered a clear indicator of its purity.

The greater the contamination in water, the lower its electrical resistance, while the purer the water, the higher its electrical resistance.

This approach satisfied everyone for a long time, until international terrorism reached the level of prevalence observed today and until general environmental pollution reached the unprecedented scale and magnitude currently being experienced.

These are certainly not all the factors determining the urgent need for more comprehensive water quality control, but they are among the most important.

Practically all existing technologies, instruments, and equipment for water quality control have a very narrow range of technical capabilities and do not cover all the parameters that need to be continuously monitored in order to prevent water from reaching consumers which, due to the reasons listed above, may be contaminated to a degree that poses a danger to human life and health.

Milk is one of the most important products in a balanced diet, and since a significant proportion of its composition is also water, it requires equivalent mobile, reliable, and accurate monitoring technologies adapted both to increasing milk quality requirements and to evolving regulatory quality standards.

When monitoring milk quality, adaptation to new technological conditions and industrial processing procedures is also of great importance.

Based on this incomplete set of information, a reasonable conclusion can be drawn regarding the necessity of continuous monitoring of the quality condition of milk and water before use.

Such technologies have been developed, and a brief description of these technologies is provided below.

1. Device for real-time monitoring of the current quality status of drinking water.

The device is intended for real-time monitoring and evaluation of the current value of a complex digital indicator of the dynamic quality status of drinking water. The device can be adapted for technological water quality control systems at process input stages and for wastewater quality monitoring before discharge into sewage systems or before returning the water to the process after regeneration.

The complex digital indicator of the dynamic state of water and aqueous solutions is an integral parameter which, based on frequency, amplitude, resistance, resonance phenomenon parameters, inductance, and a set of dynamic characteristics of the water flow, represents an integral equivalent of the current value of the content and concentration of components in water, as well as the relationships, including biological relationships, between these components and parameters.

The device for selective real-time identification of the current value of the complex digital indicator of the dynamic quality status of drinking water is a compact device designed for operation as part of water pipeline systems, water flow metering systems, or under field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for water input, output, control, and flow transformation, where the water flow transformation system includes an aerodynamic mechanism for removing gases from the specified flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

The device and its operating procedure do not require special training for the operator or user.

2. Device for real-time monitoring of the current quality status of cow's milk.

The device is intended for real-time monitoring and evaluation of the current value of a complex digital indicator of the dynamic quality status of cow's milk.

The complex digital indicator of the dynamic state of cow's milk is an integral parameter which, according to criteria of frequency, amplitude, resistance, inductance, and a set of dynamic characteristics of the milk flow, serves as an integral equivalent of the current content and concentration of components in cow's milk and the relationships, including biological relationships, between these components.

The device for its selective real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

3. Complex integral indicator of water and aqueous solution quality and a device for its real-time identification.

The digital indicator of the dynamic quality status of drinking water, which, through comparison of an impulse directed to the sensor according to criteria of frequency, amplitude, resistance, inductance, and corresponding parameters generated in the pipeline by resonance phenomena within the flow, together with a set of dynamic characteristics of the water flow, serves as an integral equivalent of the current content and concentration of components in water.

The device for its selective real-time identification is a compact device intended for operation in urban or main water supply systems or under field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the water flow supplied for monitoring, where the water flow transformation system includes an aerodynamic mechanism for gas removal from the flow.

The complex integral water quality indicator also includes a complex integral sensor indicator which, for each sensor type, its design parameters, and the signal parameters supplied to the sensor, is a constant value, as confirmed by the results of a series of tests involving more than 1,000 cycles using four types of sensors.

The device may be designed for stationary applications as well as for rapid analysis applications.

4. Complex integral indicator of cow's milk quality and a device for its real-time identification.

The digital indicator of the dynamic state of cow's milk which, according to criteria of frequency, amplitude, resistance, inductance, and a set of dynamic characteristics of the milk flow, serves as an integral equivalent of the current content and concentration of components in cow's milk.

The device for its selective real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

5. Dynamic indicator of the current value of somatic cell count in cow's milk and a device for its selective real-time identification.

The digital indicator of the dynamic state of cow's milk which, according to criteria of frequency, amplitude, resistance, inductance, and a set of dynamic characteristics of the milk flow, serves as an integral equivalent of the current content and concentration of somatic cells in cow's milk.

The device for its selective real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

6. Dynamic complex indicator of the current fat concentration value in cow's milk and a device for its selective real-time identification.

The digital indicator of the dynamic state of cow's milk which, according to criteria of frequency, amplitude, resistance, inductance, and a set of dynamic characteristics of the milk flow, serves as an integral equivalent of the current content and concentration of fat or fatty acids in cow's milk.

The device for its selective real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

7. Dynamic complex indicator of the current lactose content value in cow's milk and a device for its selective real-time identification.

The digital indicator of the dynamic state of cow's milk which, according to criteria of frequency, amplitude, resistance, inductance, and a set of dynamic characteristics of the milk flow, serves as an integral equivalent of the current lactose content in cow's milk.

The device for its selective real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, moni-

toring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

8. Complex integral indicator of mastitis in cows and a device for its real-time identification.

The digital indicator which, according to criteria of frequency, amplitude, resistance, and inductance, serves as an integral equivalent or indicator of the occurrence of mastitis in cows.

The device for its real-time identification is a compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

The device may be designed for stationary applications as well as for rapid analysis applications.

9. Device for selective real-time identification of cow's milk quality during its transportation to a collection tank after milking.

A compact device intended for operation under dairy farm conditions or in field conditions powered by solar batteries.

The device has minimal energy consumption.

The device includes functionally interconnected systems for input, output, monitoring, and transformation of the milk flow, where the milk flow transformation system includes an aerodynamic mechanism for gas removal from the milk flow.

10. Device for non-contact monitoring of cow's milk condition parameters.

The device includes systems for supplying milk for monitoring, removing the milk flow from the monitoring zone, and a sensor-based electronic integrated monitoring module with an interface.

The device may include a signal identification system and a device for rapid comparison of identified signals with a reference standard.

11. Device for simultaneous monitoring of multiple cow's milk condition parameters during transportation.

The device has two configurations.

The first configuration is intended for installation on tanks for monitoring milk quality during transportation and during transfer of milk for processing into dairy products.

The second configuration is intended for installation on flexible or rigid pipelines through which milk is directed into storage tanks; this configuration may additionally include real-time temperature measurement functions.

12. Device for rapid analysis of cow's milk quality.

The device is a mobile compact instrument with an internal chamber into which milk (or any other liquid) is introduced for analysis.

A sensor selectively tuned to a specific parameter of milk or any other liquid is positioned around the chamber.

The device does not require adjustment or calibration and has several levels of protection.

13. Device for selective rapid analysis of cow's milk quality parameters.

The device is a mobile compact instrument with an internal chamber into which milk (or any other liquid) is introduced for analysis.

A sensor selectively tuned to a specific parameter of milk or any other liquid is positioned around the chamber.

The device does not require adjustment or calibration and has several levels of protection.

14. Non-contact milk level sensors in containers.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The device has several configuration options.

It may be located inside the liquid container, outside the container, and may have different sensor configurations.

15. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of the integral milk quality indicator at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured for monitoring and evaluating the integral quality indicator of milk (or any other liquid) and as a level sensor.

The device may also simultaneously monitor any physical characteristics of milk or liquid, such as conductivity, density, and acidity level.

16. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of the somatic cell count in milk at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor the number of somatic cells and as a level sensor.

The device may also simultaneously monitor any physical characteristics of milk or liquid, such as conductivity, density, and acidity level.

17. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of fat content in milk at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor fat concentration and as a level sensor.

18. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of lactose content in milk at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor lactose concentration and as a level sensor.

19. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of blood trace content in milk at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor blood concentration and as a level sensor.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor parameters and as a level sensor.

20. Device for comprehensive monitoring of milk level in containers with simultaneous evaluation of the concentration of several basic components in milk at that level.

The device monitors the level of milk (or any other liquid) in a dedicated pipeline section connected to the container in which the liquid level is being monitored.

The specified pipeline section simultaneously serves as a resonance sensor configured to monitor parameters and concentrations of components in milk or any other liquid and includes several sensors, each configured to monitor one parameter, with each sensor simultaneously functioning as a level sensor.

21. Device for changing the turbulence level of milk flow.

The device is intended for the conversion and dynamic transformation of a turbulent

milk flow with the formation of a local laminar flow zone in which milk monitoring is performed using a resonance sensor.

In addition, during flow transformation, the device releases air from the milk flow and stabilizes its hydrodynamic characteristics.

22. Device for preparing milk flow for real-time monitoring of condition parameters.

The device is intended for the conversion and dynamic transformation of milk flow with the formation of a local laminar flow zone in which milk monitoring is performed using a resonance sensor.

23. Device for real-time monitoring of gas content levels in milk.

The device is a resonance sensor that detects changes in a set of parameters in milk depending on the concentration of air or any other gas contained in it.

The device may simultaneously monitor the filling level of the pipeline through which the milk flow moves and the turbulence level of the milk flow within the pipeline.

24. Milk aeration process control system with real-time monitoring of air content in milk.

The milk aeration process control system with monitoring of air content levels in milk includes feedback with a resonance sensor and changes the parameters of compressed air depending on the concentration of air in the milk.

The system includes a resonance sensor, an interface, and a converter that transforms sensor signals into control signals for the compressed air source, through which the pressure and flow rate of compressed air are adjusted.

The system also includes an aerodynamic function for introducing air into the milk.

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submitted 28.05.2026;
accepted for publication 12.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-128-134



**REAL-TIME MONITORING OF THE CURRENT VALUE
OF THE COW'S MILK CONDITION
(Comprehensive integrated quality indicator of cow's milk and
a device for its real-time identification. A device for monitoring
the current value of the cow's milk condition in accordance
with the concept of top-category expert – Liubov Skokova)**

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Cite: Bogomolov A. B. (2026). *Real-Time Monitoring of the Current Value of the Cow's Milk Condition. (Comprehensive integrated quality indicator of cow's milk and a device for its real-time identification. A device for monitoring the current value of the cow's milk condition in accordance with the concept of top-category expert – Liubov Skokova).* Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-128-134>

Abstract

The article discusses the development of a comprehensive integrated digital indicator of cow's milk quality and a series of devices for its real-time identification and monitoring. *Particular attention is given to the integral concept developed and proposed by Liubov Skokova, which combines artificial intelligence, artificial neural networks, and electromagnetic resonance spectroscopy for food quality control.* Within this framework, parameters such as frequency, amplitude, resistance, inductance, electrochemical characteristics, and dynamic milk-flow properties are used as an integrated equivalent of the current content and concentration of milk components. The article describes compact, energy-efficient devices designed for operation on dairy farms, in field conditions, and in stationary installations, including versions powered by solar energy and intended for rapid analysis.

Special emphasis is placed on the selective real-time identification of somatic cell concentration, fat and fatty acid content, lactose concentration, traces of blood, and indicators associated with mastitis detection. The proposed systems incorporate resonant sensors, milk-flow transformation units, aerodynamic gas-removal mechanisms, and integrated monitoring modules capable of evaluating multiple milk-quality parameters simultaneously. The article also examines methodological approaches for the detection of subclinical and clinical mastitis through the combined assessment of somatic cell counts, electrical conductivity, pH, density, viscosity, and fat content. The presented devices, systems, software solutions, and associated methods are highlighted as innovative technological developments with significant practical potential for modern dairy production and quality assurance, while demonstrating strong prospects for patent protection through combinatorial and integrative patent applications.

Keywords: *Comprehensive integrated quality indicator of cow's milk; Device for identification of the comprehensive integrated quality indicator of cow's milk; Digital indicator of the dynamic state of cow's milk, which, according to the criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, is an integral equivalent of the current content and concentration of components in cow's milk; Comprehensive Integrated Digital Indicator of the dynamic and electrochemical state of cow's milk*

Real-Time Device for Monitoring the Current State of Cow's Milk

The device is intended for the real-time monitoring and assessment of the current value of a comprehensive digital indicator of the dynamic quality state of cow's milk.

The Comprehensive Digital Indicator of the Dynamic State of Cow's Milk is an integral parameter that, based on the criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, serves as an integral equivalent of the current content and concentration of components in cow's milk, as well as the relationships, including biological interactions, among these components.

The device for the selective real-time identification of the Comprehensive Digital Indicator of the Dynamic State of Cow's Milk is a compact module designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

Comprehensive Integrated Quality Indicator of Cow's Milk and a Device for Its Real-Time Identification

The Digital Indicator of the Dynamic State of Cow's Milk is a parameter that, based on the criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, serves as an integral equivalent of the current content and concentration of components in cow's milk.

The device for the selective real-time identification of this Comprehensive Integrated Digital Indicator of the Dynamic and Electrochemical State of Cow's Milk is a com-

pact device designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

Dynamic Indicator of the Current Somatic Cell Count in Cow's Milk and a Device for Its Selective Real-Time Identification

The Digital Indicator of the Dynamic State of Cow's Milk is a parameter that, based on the criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, serves as an integral equivalent of the current content and concentration of somatic cells in cow's milk.

The device for its selective real-time identification is a compact device designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

Dynamic Comprehensive Indicator of the Current Fat Concentration in Cow's Milk and a Device for Its Selective Real-Time Identification

The Digital Indicator of the Dynamic State of Cow's Milk is a parameter that, based on the

criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, serves as an integral equivalent of the current content and concentration of fat or fatty acids in cow's milk.

The device for its selective real-time identification is a compact device designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

Dynamic Comprehensive Indicator of the Current Lactose Content in Cow's Milk and a Device for Its Selective Real-Time Identification

The Digital Indicator of the Dynamic State of Cow's Milk is a parameter that, based on the criteria of frequency, amplitude, resistance, inductance, and the set of dynamic characteristics of milk flow, serves as an integral equivalent of the current lactose content in cow's milk.

The device for its selective real-time identification is a compact device designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

Comprehensive Integrated Mastitis Indicator in a Cow and a Device for Its Real-Time Identification

The Digital Indicator is a parameter that, based on the criteria of frequency, amplitude, resistance, and inductance, serves as an integral equivalent or indicator of the occurrence of mastitis in a cow.

The device for its real-time identification is a compact device designed for operation on dairy farms or in field conditions, with power supplied by solar panels.

The device has minimal energy consumption.

The device includes functionally interconnected systems for milk input, output, monitoring, and flow transformation, wherein the milk-flow transformation system incorporates an aerodynamic mechanism for removing gases from the milk flow.

The device may be configured for stationary applications as well as for rapid analysis.

The aforementioned Comprehensive Integrated Digital Indicator of the Dynamic and Electrochemical State of Cow's Milk and the Presence of Mastitis, together with the device for its real-time measurement, have, as a patent application entitled "Device, Program, System, and Associated Method of Application," been recognized as fully patentable on the basis of an extensive patent search and may be protected through a combinatorial and integrative patent application.

Device for Non-Contact Monitoring of Cow's Milk Condition Parameters

The device includes systems for introducing milk for monitoring, removing the milk flow from the monitoring zone, and a sensor-based electronic integrated monitoring module with an interface.

The device may include a signal identification system and a unit for the accelerated comparison of identified signals with a reference standard.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Simultaneous Monitoring of Multiple Cow's Milk Condition Parameters During Transportation

The device is available in two configurations.

The first configuration is intended for installation on tanker containers for monitoring milk quality during transportation and

during the transfer of milk for dairy product processing.

The second configuration is intended for installation on flexible or rigid pipelines through which milk is directed to storage tanks. This configuration may additionally include real-time temperature measurement functions.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Rapid Analysis of Cow's Milk Quality

The device is a mobile compact instrument with an internal chamber into which milk (or any other liquid) is introduced for analysis.

A sensor selectively tuned to a specific parameter of milk or any other liquid is positioned around the chamber.

The device does not require adjustment or calibration and incorporates multiple levels of protection.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Selective Rapid Analysis of Cow's Milk Quality Parameters

The device is a mobile compact instrument with an internal chamber into which milk (or any other liquid) is introduced for analysis.

A sensor selectively tuned to a specific parameter of milk or any other liquid is positioned around the chamber.

The device does not require adjustment or calibration and incorporates multiple levels of protection.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Non-Contact Milk Level Sensors for Storage Tanks

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The device is available in several configurations.

It may be installed inside the liquid-containing tank, outside the tank, and may incorporate various sensor designs.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Evaluation of the Integrated Milk Quality Indicator at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for monitoring and evaluating the integrated quality indicator of milk (or any other liquid) and as a level sensor.

The device may also simultaneously monitor various physical characteristics of milk or other liquids, such as conductivity, density, and acidity level.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Assessment of the Somatic Cell Count in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for monitoring the somatic cell count and as a level sensor.

The device may also simultaneously monitor various physical characteristics of milk or other liquids, such as conductivity, density, and acidity level.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Assessment of Fat Content in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for monitoring fat concentration and as a level sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Assessment of Lactose Content in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for monitoring lactose concentration and as a level sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Assessment of Blood Trace Content in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for monitoring blood concentration and as a level sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.\

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Sequential Assessment of the Concentration of Basic Components in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured for parameter monitoring and as a level sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Comprehensive Monitoring of Milk Level in Storage Tanks with Simultaneous Assessment of the Concentration of Multiple Basic Components in Milk at That Level

The device monitors the level of milk (or any other liquid) within a dedicated section of a pipeline connected to the tank in which the liquid level is being monitored.

The specified section of the pipeline simultaneously functions as a resonant sensor configured to monitor parameters and component concentrations in milk or any other liquid and incorporates multiple sensors,

each configured to monitor a specific parameter, with each sensor simultaneously serving as a level sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Modifying the Turbulence Level of Milk Flow

The device is intended for the conversion and dynamic transformation of a turbulent milk flow, creating within it a localized laminar-flow zone in which milk monitoring is performed using a resonant sensor.

In addition, during flow transformation, the device releases air from the milk flow and stabilizes its hydrodynamic characteristics.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Preparing Milk Flow for Real-Time Monitoring of Condition Parameters

The device is intended for the conversion and dynamic transformation of milk flow, creating a localized laminar-flow zone in which milk monitoring is performed using a resonant sensor.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Device for Real-Time Monitoring of Gas Content in Milk

The device is a resonant sensor that detects changes in a set of parameters in milk depending on the concentration of air or any other gas contained within it.

The device may simultaneously monitor the degree of pipeline filling through which the milk flow is moving and the level of turbulence of the milk flow within the pipeline.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

Milk Aeration Process Control System with Real-Time Monitoring of Air Content in Milk

The milk aeration process control system with monitoring of the air-content level in milk incorporates feedback from a resonant sensor and adjusts the parameters of compressed air according to the concentration of air in the milk.

The system includes a resonant sensor, an interface, and a converter that transforms signals from the sensor into control signals for the compressed-air source, through which the pressure and flow rate of the compressed air are adjusted.

The system also incorporates an aerodynamic function for introducing air into the milk.

The aforementioned device, program, system, and associated method of application have, on the basis of an extensive patent search, been recognized as fully patentable and may be protected through a combinatorial and integrative patent application.

On the Methodology for Monitoring a Cow's Condition for the Presence of Subclinical Mastitis and Mastitis with Evident Clinical Signs:

The primary parameter indicating the presence of mastitis is the somatic cell count in milk.

In cases of subclinical mastitis, which occurs much more frequently, monitoring the somatic cell count alone is generally insufficient. It is necessary to monitor a number of additional parameters that, together with an elevated somatic cell count, characterize the condition associated with so-called subclinical mastitis.

In such cases:

- Milk viscosity decreases.
- The chloride-sugar index increases.
- Electrical conductivity increases.
- pH increases to 6.83–7.19.

- Density decreases to 1.024–1.025 (compared to the normal value of 1.027).
- Fat content decreases.

Milk samples will be supplied in three specimens from each milking of a single cow – the initial stage of milking, the middle stage of milking, and the final stage of milking.

The samples differ from one another in all constituent parameters, such that milk from the initial stage of milking is the least concentrated, while milk from the final stage of milking is the most concentrated.

For the first series of experiments, the following is proposed:

1. Comparison of the three milk samples with one another using the integrated indicator.
2. Addition of sugar to the samples.

3. Addition of glucose to the samples.
4. Monitoring of electrical conductivity.
5. Monitoring of pH.
6. Monitoring of fat content.
7. Monitoring of viscosity.
8. Monitoring of density.
9. Addition of carbamide (urea).
10. Addition of blood.

(Based on these results, an analytical report should be prepared and coordinated with leading institutes and university laboratories.)

The three samples should be stored at room temperature for 1 day, 3 days, and 5 days, after which the tests should be repeated.

All of the above experiments may be conducted prior to the receipt of specialized laboratory instruments intended for verification testing.

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submitted 12.05.2026;
accepted for publication 26.05.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-135-142



**COMPOSITIONAL ENGINEERING SOLUTIONS AS THE PRIMARY
INSTRUMENT OF TECHNOLOGICAL INTEGRATION IN THE
PHARMACEUTICAL INDUSTRY
(Psychological Barriers and Compositional Engineering Solutions
as an Essential Foundational Component for the Development
of Integrative Pharmaceutical Inventions: Compositional
Engineering Solutions as the Primary Instrument of Technological
Integration in Smart Pharmaceutical Manufacturing)**

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Cite: Gladilina T. (2026). *Compositional Engineering Solutions as the Primary Instrument of Technological Integration in the Pharmaceutical Industry. (Psychological Barriers and Compositional Engineering Solutions as an Essential Foundational Component for the Development of Integrative Pharmaceutical Inventions: Compositional Engineering Solutions as the Primary Instrument of Technological Integration in Smart Pharmaceutical Manufacturing).* Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-135-142>

Abstract

This publication examines the role of technological innovation in modern pharmaceutical manufacturing, with particular emphasis on the implementation of advanced production technologies, the application of novel materials, and the replacement of conventional manufacturing methods with unconventional engineering solutions capable of achieving technological breakthroughs, improving production efficiency, and supporting the transition toward smart pharmaceutical manufacturing.

The study demonstrates that the process of technological innovation may vary considerably depending on the existing technical culture, technological maturity, and initial level of industrial development within a particular manufacturing environment. Nevertheless, the necessity of initiating and continuously advancing innovation processes has become an essential prerequisite for maintaining industrial competitiveness and sustainable technological development.

Particular attention is devoted to the global transformation of industrial economies toward innovation-driven production systems. While the earliest stages of technological breakthroughs were primarily associated with high technologies, microelectronics, and nanotechnology, contemporary innovation has expanded to encompass traditional industrial sectors, including energy, healthcare, pharmaceuticals, transportation, and other fundamental industries that directly influence modern society.

The publication further emphasizes that, in order to enhance the competitiveness of their products and manufacturing technologies, industrial enterprises must continuously seek new approaches for improving production efficiency, reducing energy consumption and operating costs, increasing environmental sustainability, and strengthening the long-term economic stability of manufacturing operations.

Special emphasis is placed on the growing importance of compositional engineering solutions in the design, evaluation, and validation of advanced technological systems. Such engineering approaches are increasingly becoming fundamental elements of industrial design methodology and constitute one of the principal instruments for the development of innovative pharmaceutical technologies and integrated smart manufacturing systems.

Keywords: *Compositional engineering solutions in smart pharmaceutical manufacturing and the production of pharmaceutical equivalents; Implementation of advanced technologies in pharmaceutical manufacturing; The primary instrument of technological integration in smart pharmaceutical manufacturing; Principles and criteria of industrial design; Integrative inventions in the pharmaceutical industry; Reliability of novel pharmaceutical products; Methods and approaches for developing a compositional engineering framework for innovative technological solutions*

Introduction

The illustrations presented in this publication demonstrate the evolutionary development of one of the compositional engineering solutions that has served as the foundation

for a series of integrative inventions aimed at optimizing the Brayton thermodynamic cycle, with the prospect of its transition to the Humphrey thermodynamic cycle.

Figure 1.



Evolution of Industrial Design Principles and Criteria

The implementation of advanced smart technologies, the application of novel materials, and the replacement of conventional manufacturing methods with unconventional engineering approaches that facilitate technological breakthroughs and significantly improve production efficiency are now widely recognized as the innovation process.

The nature of this process may differ considerably depending on the existing

technical culture, technological capabilities, and the initial level of industrial development from which innovation is initiated. Nevertheless, there is no doubt that the need to initiate and continuously advance innovation has become an essential prerequisite for sustainable industrial development.

During recent years, the economies of virtually all industrialized countries have increasingly evolved toward innovation-driven development.

Whereas the earliest technological breakthroughs were primarily concentrated in high technologies, microelectronics, and nanotechnology, contemporary innovation is becoming progressively focused on traditional engineering disciplines, including conventional manufacturing technologies, energy systems, healthcare, transportation, and other fundamental sectors that support modern society.

To enhance the competitiveness of their products and technologies, industrial enterprises are continuously compelled to identify

new approaches for improving manufacturing efficiency, reducing energy consumption and operating costs, increasing environmental sustainability, and strengthening the long-term economic stability of individual companies and manufacturing facilities.

The emergence of new capabilities for the design, engineering analysis, and validation of technical solutions has also introduced compositional engineering design principles, which are increasingly becoming fundamental criteria within the methodologies and tools of modern industrial design.

Figure 2.



A New Perspective on Product Durability

Until recently, product durability was regarded as one of the principal criteria determining its commercial value. Today, however, the time interval between the market introduction of a new product and the launch of its next-generation or upgraded successor has become so short that, in many cases, there is little justification for concentrating excessive effort, time, and financial resources on achieving a level of durability that substantially exceeds the actual commercial life cycle of the product.

Since the duration of this market cycle varies significantly across different categories of products, the concept of durability itself becomes increasingly relative and, as an objective of an invention, is no longer necessarily a critical factor.

There is also a subjective aspect of product durability that should be taken into consideration. Market expectations regarding the service life of particular product categories influence numerous commercial factors, including production volumes, sales volumes, and product pricing. If an engineering solution significantly increases product durability, the demand for replacement products

may decline while the price consumers are willing to pay remains unchanged.

As a consequence, manufacturers may experience reduced sales volumes and become faced with a strategic choice: either embrace the innovation or attempt to prevent its implementation and commercialization. Practical experience demonstrates that many companies choose the latter approach, thereby obstructing the introduction of innovations. In such situations, the principal party affected is often the inventor, whose technological solution may ultimately be rejected by the market despite its technical superiority.

A New Perspective on Product Reliability

The concept of product reliability and the criteria used for its evaluation are also undergoing fundamental transformation. Of particular importance is the relationship between product reliability and the manufacturer's warranty obligations to the customer. In many cases, the cost of fulfilling warranty commitments is comparable to the manufacturing cost of the product itself.

Consequently, reliability becomes one of the key factors determining the commercial success of an invention, in combination with

the technical and operational advantages achieved through its implementation.

Here again, the time factor plays a significant role. Reliability that substantially exceeds the actual commercial life cycle of a product may become economically disadvantageous, resulting in a highly reliable product that is commercially unattractive for the manufacturer.

New Opportunities for Systematic Prior-Art Search and Novelty Assessment.

Modern information technologies provide fundamentally new opportunities for conducting systematic prior-art searches and evaluating the novelty of newly developed technical solutions.

Suppose that, during the preliminary design of a compositional engineering solution, it becomes necessary to integrate several conventional engineering solutions together with newly developed digital technologies within a single horizontal integration level. Subsequently, the design may require a higher level of integration involving software algorithms, digital platforms, and communication interfaces connecting the various technological levels.

In such circumstances, an important question arises: how should the prior-art search be organized, which technological directions should be investigated, and how can existing analogues of the proposed compositional solution be identified most effectively?

A practical approach is to begin the patent search after the overall composition has been defined by decomposing the proposed system into its independent and autonomous technical solutions.

Once this decomposition has been completed, it is advisable to identify one fun-

damental technical solution as the baseline configuration. The prior-art search should first be conducted for this baseline solution and then progressively expanded by sequentially incorporating each additional technical solution included within the overall composition until the complete integrated configuration has been analyzed.

New Opportunities for Evaluating the Practical Value and Feasibility of Modifying Existing Technical Solutions

It is often said that the new is well-forgotten old.

For this reason, before initiating the innovation process and commencing the synthesis of a new product, it is advisable to determine whether individual functional elements of the proposed composition have already been invented.

If such a solution – or an equivalent technical solution – is identified, the introduction of new materials, modern components, and digital monitoring and control systems may enable the development of an entirely new technological composition capable of integration into engineering systems of a higher hierarchical level.

The Impossibility of Successful Commercialization Without the Formation of Compositional Principles and a Compositional Structure.

Practical experience demonstrates that the commercial sale or licensing of autonomous technical solutions is extremely unlikely unless these solutions have been designed from the outset for integration into technological systems or engineering solutions of a higher functional level.

Figure 3.



By contrast, inventions possessing a compositional engineering structure, in which a conceptual framework for integration into higher-level technological and engineering systems has already been established, are generally commercialized more successfully and within a significantly shorter period. This is because investors, industrial partners, and prospective licensees are provided not only with the technical solution itself but also with the methodology and engineering principles governing its integration into larger technological systems, as described in both the patent specification and the patent claims.

Proposed Methods and Approaches for Developing a Compositional Engineering Framework for Innovative Technical Solutions.

Compositional Engineering Solutions as a Design Methodology for Technology Integration.

Accordingly, the compositional nature of an engineering solution may be regarded as a design-oriented engineering methodology for developing new technical solutions with the objective of integrating them into existing technological systems and engineering configurations.

Since the methodology of such integration may itself be unique and possess substantial novelty, both the specification and the patent claims of a composition-based invention – characterized by a multi-level architecture of cause-and-effect relationships between the components of the composition and by distinguishing features integrated into its engineering and technological structure – largely determine the commercial success of the resulting innovation.

Methods for Transitioning from a Compositional Engineering Foundation to an Integrative Invention

An engineering and technological composition frequently requires additional – and often fundamentally new – relationships between its individual components and elements. In other words, even when a clearly defined engineering composition has been established, transforming it into a commercially viable innovative product requires identifying effective approaches for integrating that composition into a final product possessing multiple levels of technological integration.

Such integration strategies may vary considerably; however, the essential objective is to achieve an unprecedented improvement in performance or quality as the direct result of integration.

Influence of Patent Claim Limitations on the Protection of Compositional Engineering Solutions.

Limitations on the number of patent claims generally make it more difficult to achieve comprehensive legal protection of an invention. Nevertheless, a properly developed principle of compositional engineering may significantly strengthen both the scope and effectiveness of patent protection.

The ideal approach is to establish a system of cause-and-effect relationships through which the declared technical effect can be achieved only within the proposed system of compositional interconnections, under clearly defined conditions and through distinguishing features that determine both the structure of the composition and the independent functions of each of its constituent elements.

Because patent claims are necessarily limited in length and structure, it is advisable to include only those features and relationships that arise specifically from the interaction of the components within the composition, while avoiding the repetition of already known independent characteristics and functions of the individual elements.

Accordingly, when properly selected components are integrated within a newly developed technological system, they create a new integrated system of characteristics, functional relationships, feedback mechanisms, and operational functions that exist exclusively within that particular composition and that possess the potential for further internal development and optimization.

Adherence to these principles enables the inventor, within the limitations imposed on the number of patent claims, to concentrate exclusively on the essential distinguishing characteristics of the composition while simultaneously maximizing both the level of patent protection and the clarity of the inventive concept.

Proposed Structure of an Independent Patent Claim Based on a Compositional Engineering Solution.

Based on the author's practical experience and the recommendations of patent

specialists, an independent patent claim describing a compositional invention should consist of at least three principal sections.

The first section defines the commercial essence of the compositional invention and explains the purpose and necessity of the compositional integration. It should include:

- a clear statement of the objective of the composition;
- definition of the functional relationships within the composition and justification of the necessity of each component for its effective operation;
- formulation of the title of the composition.

The second (limiting) section contains the fundamental technical information describing the invention itself. It includes the characteristics of the basic engineering solutions incorporated within the individual components of the composition that, at the stage of drafting the patent application, are not regarded as possessing substantial novelty in their engineering, technological, or functional characteristics.

The third (characterizing) section defines the novel features of the invention, including the individual components, their interrelationships, construction materials, integrative elements, associated software products, and their underlying algorithms. Each of these elements, individually or in combination, contributes to the substantial novelty of the composition-based, multi-level integrated engineering solution.

Proposed Structure of a Dependent Patent Claim Based on a Compositional Engineering Solution

The limitation imposed on the number of patent claims assigns a specific strategic role to each individual dependent claim in establishing and protecting the novelty of the invention.

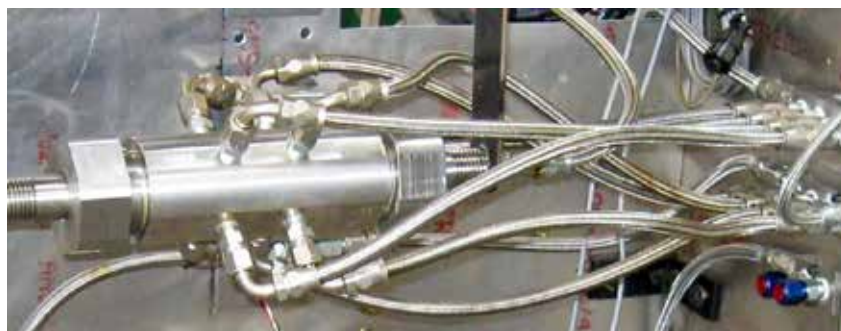
Accordingly, the second (limiting) section of a dependent claim should contain all essential local and application-specific technical information describing the invention, including the characteristics of the conventional engineering solutions incorporated within the corresponding components of the composition that are not considered to possess substantial novelty.

The third (characterizing) section should contain localized and application-specific information describing the technical details of the individual components, their interrelationships, construction materials, integrative elements, associated software products, and their principal algorithms. Each of these elements, individually or in combination, provides localized elements of substantial novelty that contribute to the overall composition-based, multi-level integrated engineering solution.

Proposed Methodology for Designing Prototypes of Compositional Engineering Solutions

The proposed methodology for prototype development enables the validation and experimental verification of each innovative element incorporated within the compositional engineering solution.

Figure 4.



Design of Prototypes for Compositional Engineering Solutions

The design of a prototype or experimental model of an innovative composition-based product is most effectively performed using

professional computer-aided design (CAD) software together with its engineering analysis modules. The author prefers the SolidWorks software platform because it enables the development of a fully functional digital

model of a compositional engineering solution and allows verification of its operating cycle through engineering simulation without the need for costly prototype fabrication and experimental testing.

Analysis of Prior Art and Prototype Engineering Solutions

If the prior-art search identifies existing engineering solutions that may, at the preliminary stage, be regarded as analogous or prototype solutions for the proposed compositional engineering invention, these solutions should be evaluated in various configurations and combinations together with the additional components and functional ele-

ments incorporated into the proposed composition.

Where digital representations of such prototype or analogous engineering solutions are available, it is advisable to reconstruct their engineering models using SolidWorks and perform digital simulations of their operating cycles. The simulation results may then be directly compared with the corresponding operating characteristics of the proposed composition-based engineering solution, thereby enabling a comprehensive technical evaluation of the inventive concept and its distinguishing features.

Examples of Compositional Engineering Solutions Successfully Adopted by the Market.

Figure 5.



Examples of Compositional Engineering Solutions Successfully Adopted by the Market

Well-known examples of compositional engineering solutions include many of today's computing devices, communication systems, tablet computers, and numerous other prod-

ucts intended for both mass-market and specialized applications. The ambiguity of the language used in patent applications covering the highly complex engineering solutions underlying these products has led – and continues to lead – to numerous patent disputes and patent litigation.

Figure 6.



Figure 7.



Figure 8.



The broader application of compositional engineering solutions, together with their integrated extensions and subsequent technological interpretations, has the potential to reduce the complexity of patent-related disputes and facilitate the successful commercialization of innovative products.

Among the most prominent examples of compositional engineering solutions are the

smartphones developed by Apple Inc. Owing to their highly integrated compositional architecture and seamless integration with virtually every component of the existing information infrastructure, these multifunctional devices have demonstrated unprecedented commercial success in global markets.

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submitted 10.05.2026;

accepted for publication 24.05.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-143-151



**NEW SMART MANUFACTURING TECHNOLOGIES.
(Methods and devices for non-contact electromagnetic
resonance testing; various high-efficiency electrochemical
processing methods, including high-speed metallization
technology and water extraction from air)**

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Cite: Gudolin O. (2026). *New Smart Manufacturing Technologies. (Methods and devices for non-contact electromagnetic resonance testing; various high-efficiency electrochemical processing methods, including high-speed metallization technology and water extraction from air).* Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-143-151>

Abstract

The article examines the development of New Smart Manufacturing Technologies based on the integration of digital solutions, innovative materials, and advanced production methods. It demonstrates how TRIZ principles and the pursuit of the Ideal Final Result can improve manufacturing systems and processes. Particular attention is given to intelligent technologies, including non-contact electromagnetic resonance monitoring of water and process solutions in real time.

The article also presents practical applications such as seawater desalination through high-speed electrochemical salt deposition and water production from atmospheric air. It concludes that the integration of digital modeling, intelligent sensor systems, and innovative engineering solutions enhances efficiency, sustainability, and automation while creating new opportunities for modern industrial development.

Keywords: *Technologies; Smart technologies; Smart manufacturing technologies; Current level of manufacturing process development; Classical methods of processing raw materials, digital technologies, and new composite materials; Non-contact electromagnetic resonance testing; High-speed metallization technology; The process of achieving the ideal final result; Auxiliary materials and tools whose combined use makes it possible to approach the achievement of an ideal final result; Globalization of manufacturing processes; The expansion of areas of application follows a fan-shaped pattern and gradually spreads to numerous related processes, including both manufacturing and all auxiliary operations and processes*

At the current stage of manufacturing process development, characterized by the extensive integration of digital technologies

and new composite materials into traditional methods of raw material processing, it is extremely important to manage these additions

properly and to fully utilize the advantages they provide in the pursuit of the Ideal Final Result.

As is well known from the classical Theory of Inventive Problem Solving (TRIZ) and its further development – the Algorithm for Inventive Problem Solving (ARIZ) – an innovative approach to the systematic development of manufacturing processes offers a number of tools whose combined application makes it possible to approach the achievement of an Ideal Final Result that is as close as possible to the ideal inherent in each technology or device.

The emergence of new components in process schemes and fundamentally innovative solutions has made it possible, through proper integration methods and carefully selected implementation options, first, to reformulate the very concept and criteria of the Ideal Final Result and, second, to refine the criteria and characteristics that define this concept.

Under the conditions of globalization of manufacturing processes and the transition of the world's most developed economies to innovation-driven models of development and operation, it must be acknowledged that, in order to navigate new and not always positive production trends correctly, it is necessary to reconsider both the principles governing the organization and formation of manufacturing processes and the declared goals and objectives of those processes.

In some countries, this new approach to production organization, which incorporates the latest achievements and opportunities for improving all stages of manufacturing as well as the requirements for the development of production equipment, has been termed **New Smart Manufacturing Technologies**.

As demonstrated by the first practical experiences in the formation, design, and, most importantly, implementation of so-called new smart manufacturing technologies in industrial complexes, this process tends to gradually expand the application of original innovative technical solutions to an increasing number of complex production tasks.

This expansion follows a fan-shaped pattern, gradually spreading to numerous related processes, including both manufacturing operations and all auxiliary operations and processes, such as quality control.

As an example, one may cite the gradual spread of real-time non-contact monitoring technologies and principles, which can confidently be classified as smart technical solutions that fundamentally transform monitoring techniques and technologies while continuously improving measurement accuracy.

The implementation of this technology began in agriculture, where the need for such monitoring was driven by new requirements and increasing demands on water quality, particularly in irrigation projects.

Due to its high relevance and demand, the implementation process initially focused on monitoring acidity levels.

1. Acidity level monitoring – the following key features were taken into account and considered:

The range of acidity level monitoring in water and aqueous solutions using non-contact resonance monitoring methods is unlimited.

The monitoring accuracy can be adjusted as required, but is no less than 0.1 acidity units in accordance with the accepted standard.

The monitoring accuracy does not depend on the concentration of organic substances in the water or aqueous solution, nor does it depend on the aggressiveness of the solution, since all monitoring operations are performed remotely without any contact with the monitored liquid.

Since the highest water consumption occurs in irrigation systems, where fertilizers and other chemical reagents are introduced into the water, the next expansion of the technology's application involved monitoring the concentration of nutrients and fertilizers in irrigation solutions.

If the substances to be introduced into the nutrient solution are known in advance, the integrated sensor includes a number of selective sensors corresponding to the number of components in the solution.

Each of these sensors is configured to monitor a single component.

The measurement accuracy is within 0.5 milligrams per liter.

Since the conductivity of water and aqueous solutions largely determines their quality, the next stage of technology deployment involved its application to the monitoring of water and aqueous solution conductivity.

2. Water and aqueous solution conductivity monitoring.

Conductivity monitoring is similar to acidity level monitoring.

For successful implementation, a measurement accuracy within 1 microSiemens is sufficient.

A logical continuation of the implementation process was the development of methods and techniques for comprehensive integrated quality monitoring of liquids and aqueous solutions.

3. Comprehensive integrated quality monitoring of liquids and aqueous solutions.

Two methods are proposed for comprehensive monitoring.

The first method involves the use of only one sensor, which provides an indication of an integrated water or liquid quality parameter.

The second method involves installing a number of sensors corresponding to the number of monitored parameters or materials, with each sensor monitoring the condition or concentration of only one specific material.

The success of the third stage of technology deployment determined the strategy for its further expansion into the field of monitoring heavy metal concentrations in liquids and aqueous solutions.

4. Monitoring of heavy metal concentrations in liquids and aqueous solutions.

Monitoring can be carried out in a general mode; in this case, the sensor provides an indication of the presence of all metals in the water or aqueous solution.

Monitoring can also be performed selectively; in this case, the integrated sensor module must include sensors configured to monitor the concentration of each individual metal separately.

The sensor module may also include sensors for comprehensive monitoring of the condition and quality of water or aqueous solutions, providing simultaneous monitoring of all quality parameters.

Since organic substances are currently used as components in many water-based process solutions, a logical continuation of the expansion of non-contact measurement technology has been its further implementation in monitoring the level or concentration of organic substances in water-based process solutions.

5. Monitoring of the level or concentration of organic substances in aqueous solutions.

Monitoring of organic substance concentrations may be performed in a general mode, for example by measuring the total concentration of all organic materials and compounds in water or an aqueous solution.

Monitoring may also be selective; in this case, the integrated sensor module must include selective sensors configured for each individual organic component.

The methodology for monitoring biological components in water or aqueous solutions, due to the complete absence of contact during measurement, eliminates the possibility of measurement distortion.

Although there are many instruments and technologies available for temperature monitoring, the non-contact monitoring method makes it possible to implement an active temperature monitoring system in production lines of any complexity. Most importantly, it does not require the insertion of a temperature sensor into equipment such as an electrochemical reactor or any other complex chemical reactor.

6. Temperature monitoring of aqueous solutions.

Temperature monitoring of aqueous solutions is analogous to conductivity monitoring.

For the use of water and aqueous solutions in advanced manufacturing processes, and especially in photolithography production lines, including those involving silicon wafers, the dielectric permittivity parameter is of critical importance, particularly for automated process quality monitoring. Therefore, this group of technologies has been further extended to systems and methods for monitoring the dielectric permittivity of water and aqueous solutions.

7. Monitoring of the dielectric permittivity level of water and aqueous solutions.

Monitoring of dielectric permittivity is analogous to monitoring the level or concentration of organic substances in water and aqueous solutions.

All monitoring options are implemented using selectively configured sensors or groups of sensors installed on the outer surface of a pipeline or supplied as part of a pipeline section integrated into an existing pipeline.

During project implementation, software will be developed to identify sensor signals and interpret the concentration of the monitored parameter in water or an aqueous solution.

During the project, a range of sensor sizes will be developed for installation on pipes with diameters ranging from 10 to 120 millimeters.

The sensor manufacturing technology will also be optimized to achieve an acceptable cost level for comprehensive water and aqueous solution quality monitoring systems used in agriculture.

Further development of sensor designs and monitoring methodologies has made it possible to consider the creation of applications for a specialized device intended for non-contact verification of drinking water compliance with environmental and public health standards.

8. Applications of a device for non-contact monitoring of drinking water compliance with standards.

The device is available in two main versions. The first version is intended for installation directly on a pipeline before a tap within residential premises. The second version is portable and is designed for taking a water sample from a tap into a section of pipeline on which the sensor is installed.

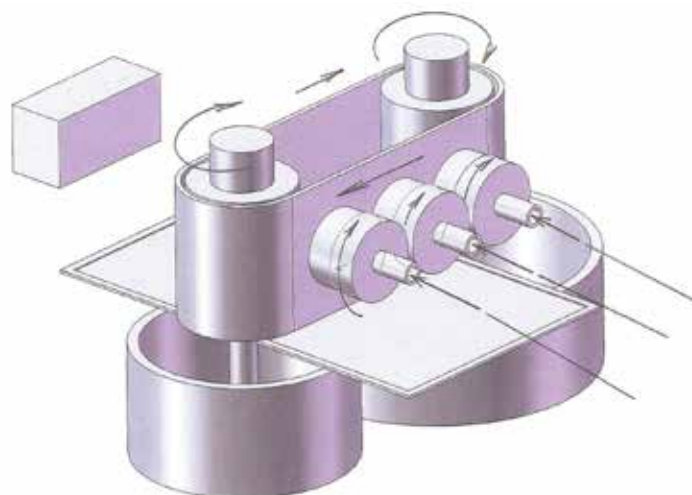
Both versions of the product feature a simple design, are manufactured from plastic, typically polyvinyl chloride (PVC), and are compact and easy to use.

The operating principle of both versions is based on comparing the reference signals of a resonance sensor with the signal obtained from a test measurement. The reference signal is obtained from water that fully complies with established standards. The sensor detects even the slightest deviations from the reference signal. The sensitivity threshold is 0.000000005 grams for metals, 0.00000000001 grams for radioactive isotopes, 0.000001 grams for hardness salts and silicates, and 0.0000001 grams for organic acids and compounds, including phenols, traces of surfactants, detergents, and mineral fertilizers. All specified concentrations are calculated per one liter of water.

The device does not selectively identify or record each individual contaminant or impurity. However, due to its high sensitivity, it can detect contamination levels corresponding to 50% of the threshold considered hazardous to human health in drinking water. This high level of accuracy allows continuous monitoring of water quality for domestic use and enables corrective measures to be taken before contamination reaches dangerous levels.

Public health standards in most developed countries recommend continuous water quality monitoring. The implementation of this requirement is often limited by the lack of reliable, user-friendly, and accurate devices available at a price suitable for widespread adoption.

Figure 1. Block diagram of a seawater desalination module utilizing the method of high-speed electrical salt deposition onto a moving permeable cathode made of a composite carbon-carbon fabric



The proposed versions of the device fully comply with applicable standards, both in terms of the safety of the materials used and the effectiveness of their operation.

Both versions are easy to manufacture, do not require any special production technologies, and can be produced under the conditions of small-scale enterprises while maintaining an optimal price level.

This makes it possible to localize production and assembly near the point of sale, reducing transportation costs and enabling direct distribution without the need for warehouse storage, thereby minimizing associated expenses.

The foregoing demonstrates that the implementation of so-called smart elements of manufacturing technologies in one area and within one group of technologies immediately creates demand for their application in other areas and technological fields.

To further illustrate this phenomenon, an example is presented of the application of an innovative smart high-speed metallization technology as a core technology for seawater desalination, replacing the conventional

technology based on reverse osmosis membranes.

As can be seen from the three-dimensional model of the seawater desalination module, water is supplied to three rotating anodes, through which it is delivered to a moving cathode made of carbon-carbon fabric.

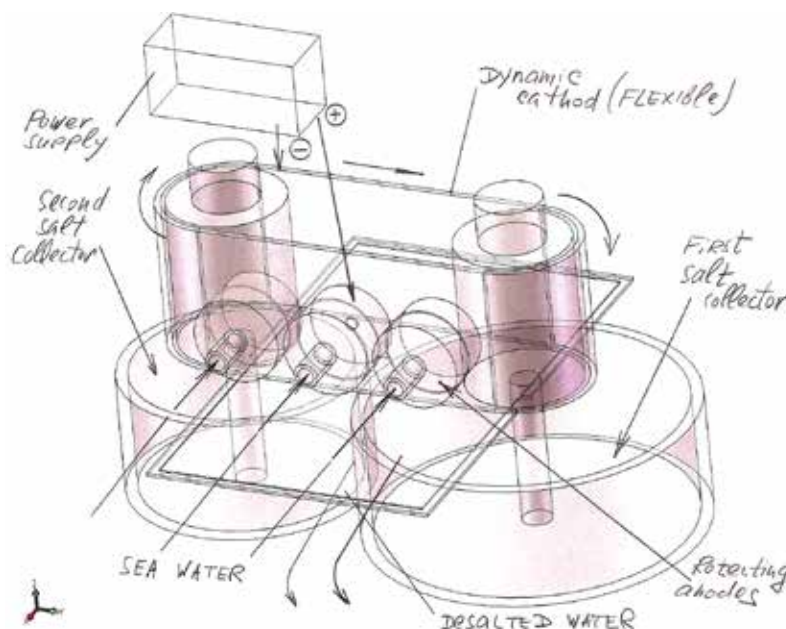
The module performs a complete cycle of high-speed electrical deposition of salt from seawater (a natural electrolyte) onto the conveyor-type cathode.

As the conveyor belt approaches the drums, the deposited salt falls from the cathode into a salt collection container.

This technology addresses one of the major challenges associated with reverse osmosis desalination, namely the discharge back into the sea of highly concentrated brine containing the salt removed from the desalinated water.

In addition, unlike membrane-based reverse osmosis technology, this approach makes it possible to construct an efficient and autonomous desalination module with a capacity of, for example, 50 cubic meters of desalinated water per hour.

Figure 2. The figure shows a model of a seawater desalination module employing the method of high-speed electrical deposition with complete recovery of the salt contained in seawater in dry form



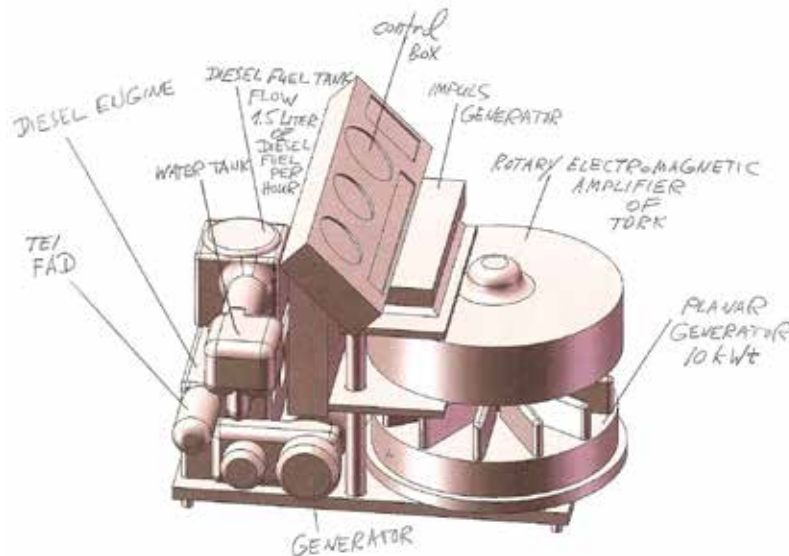
As noted above, the application of innovative high-speed electrolytic coating technology (characteristic of automated production lines and flexible automated manufacturing

modules in microelectronics) makes it possible to create a new group of innovative products in a scale and size range previously unavailable to the market. This, in principle,

confirms the validity of the concept advocating the widespread adoption of manufacturing system design principles based on the methods of New Smart Manufacturing Technologies.

To further illustrate this concept, let us consider a sequence of developments in air-to-water production technology aimed at incorporating the characteristic features inherent in **New Smart Manufacturing Technologies**.

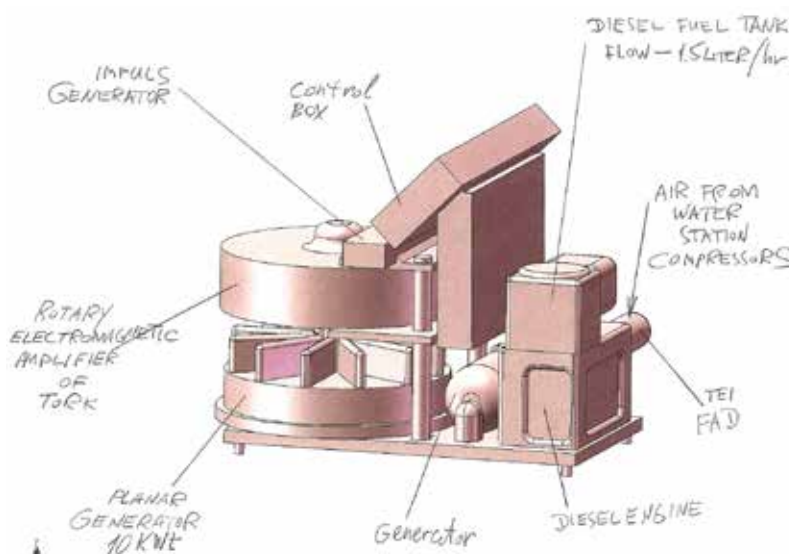
Figure 3. The figure presents a three-dimensional model of an innovative diesel generator module containing several innovative components that create entirely new operating conditions and performance outcomes in water production systems based on atmospheric moisture condensation



The diesel generator module is also adapted for use with an automatic emulsion preparation system and online fuel homogenization. In the presented configuration, this combination provides several important ad-

ditional benefits, including reduced nitrogen oxide emissions in the exhaust gases, lower fuel consumption, increased torque output, improved vibration stability of the unit, and reduced aerodynamic noise levels.

Figure 4. The figure presents a three-dimensional model of a diesel generator in which a number of the effective innovative technologies described above have been integrated, including a planar generator and a rotary electromagnetic pulse amplifier



The diesel engine of such a module is adapted to operate on a fuel emulsion, with the emulsion being prepared using water produced by the installation itself, while the energy required for the installation is generated and supplied by this module.

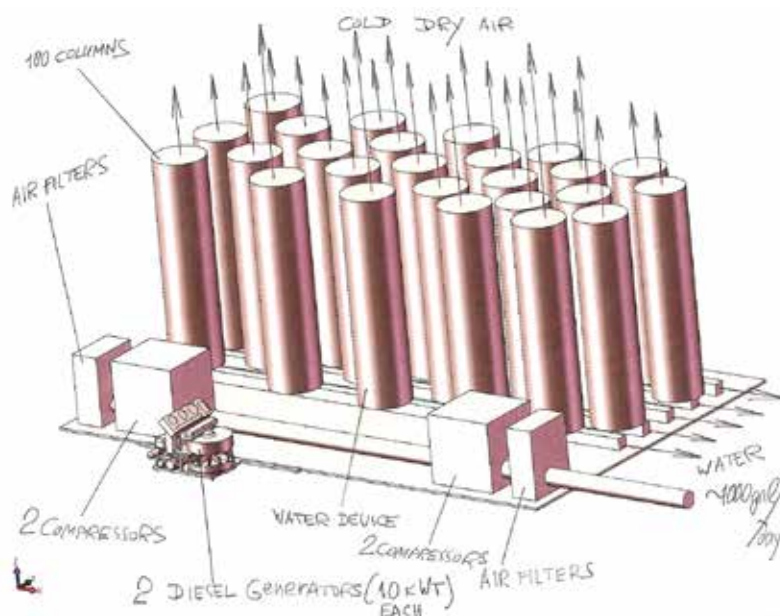
The novelty of this integrated technical solution lies in several design and configuration aspects.

The characteristics of the so-called smart technology are achieved through the combination of a number of diverse innovative elements. Their novelty is reflected in the application of multiple inventions, each of which individually, and all of which collectively, create a package of innovative advantages over conventional technologies.

For example, the use of a rotary torque amplifier operating according to the Otto principle in combination with a planar generator that maintains efficiency even at low rotational speeds makes it possible to increase power output by at least 10%. In addition, the use of a fuel emulsion in the diesel engine significantly reduces exhaust gas toxicity while also reducing fuel consumption by at least 10%.

As a further development of this system, additional air may be supplied to the emulsion preparation unit, transforming a conventional incompressible emulsion into a compressible emulsion. This provides additional fuel savings while significantly reducing the concentration of nitrogen oxides in the exhaust gases.

Figure 5. The figure presents a three-dimensional model of an industrial modular installation for water production by means of condensation from atmospheric air



The presented installation is intended to utilize universal diesel generators, the operating principles and advantages of which have been described above.

As can be seen from the system models, the application of so-called smart manufacturing technologies makes it possible to develop, for example, an industrial system for producing water from atmospheric air with minimal specific energy consumption and minimal environmental impact.

Thanks to the possibility of end-to-end computer modeling, such a system can be configured with optimal technical parame-

ters and, when necessary, can optimally adapt these parameters to existing external factors such as atmospheric pressure at the installation site, ambient humidity, air temperature in the operating area, and similar conditions.

The list of modeled parameters and combinations of modeled objects may also include many additional characteristics and technical performance indicators of the system components.

In addition to the primary operating parameters of the system, modeling can provide the ability to develop highly accurate maintenance schedules, including preventive

maintenance plans, replacement schedules for consumable parts and mechanisms, as

well as quality control schedules for the water produced.

Figure 6. The figure shows an industrial modular installation for water production by means of condensation from atmospheric air, plan view

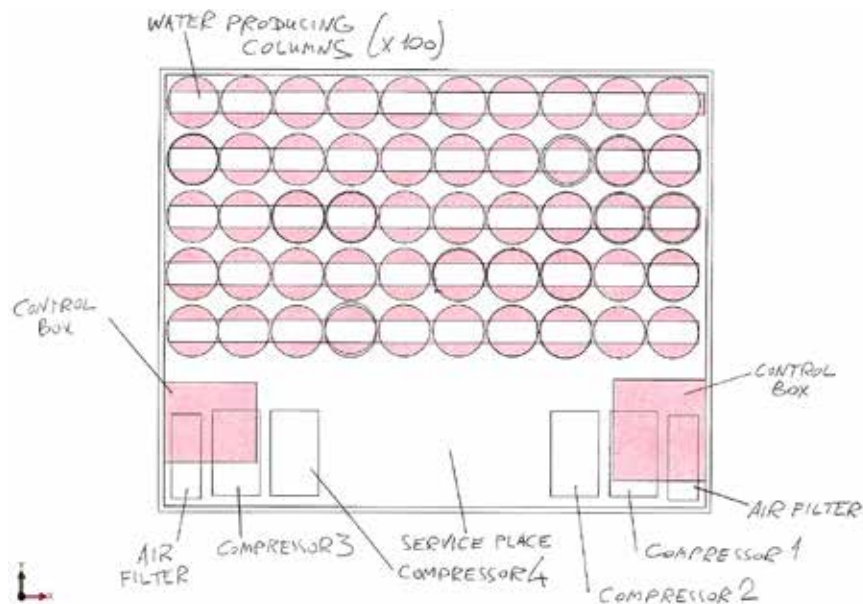
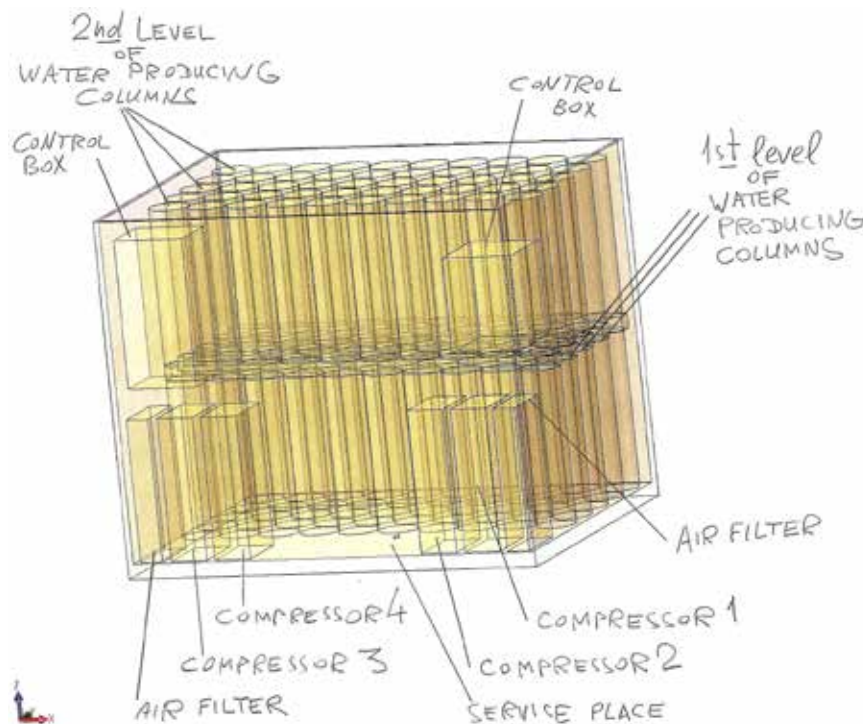


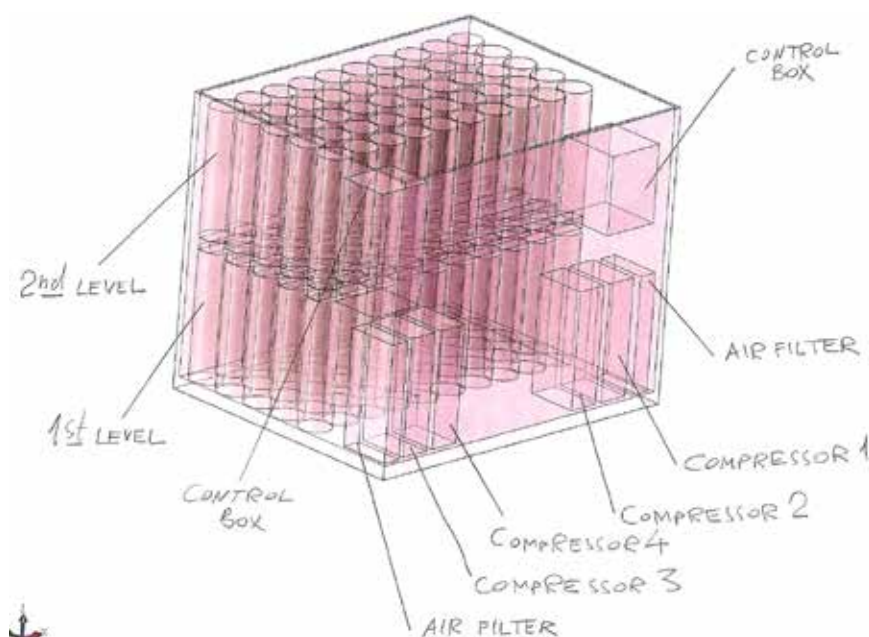
Figure 7. The figure presents a new configuration option for vertical aggregation and a significant reduction in the production area required for the installation of this integrated equipment, which forms part of a water production complex and has reserve capacity for supplying surplus electrical energy to other consumers



In conclusion, it can and should be noted that New Smart Manufacturing Technologies have a positive impact on the comprehensive development of virtually all manufacturing

systems and equipment, as well as on their combinations and configurations developed through both vertical and horizontal integration.

Figure 8. The figure shows the structure of a two-level system for producing water from atmospheric air, with the constituent components identified



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submitted 26.05.2026;
accepted for publication 10.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-152-158



INTEGRATED COMPREHENSIVE WATER TREATMENT MODULE AT THE WATER SUPPLY SYSTEM INLET

(Electrochemical treatment of industrial wastewater for the removal of heavy metal ions and enabling the repeated reuse of treated water in an autonomous recirculation mode, including in autonomous water treatment systems within the infrastructure of a smart mobile home and its structural equivalents)

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Cite: Khabarova A. (2026). *Integrated Comprehensive Water Treatment Module at The Water Supply System Inlet. (Electrochemical treatment of industrial wastewater for the removal of heavy metal ions and enabling the repeated reuse of treated water in an autonomous recirculation mode, including in autonomous water treatment systems within the infrastructure of a smart mobile home and its structural equivalents). Austrian Journal of Technical and Natural Sciences 2026, No 5–6.* <https://doi.org/10.29013/AJT-26-5.6-152-158>

Abstract

The article examines an electrochemical technology for the treatment of industrial wastewater aimed at removing heavy metal ions and enabling the repeated reuse of treated water in autonomous recirculation systems. The study reviews major sources of heavy metal contamination and evaluates existing treatment methods, demonstrating that conventional approaches do not fully address the challenges of water regeneration and reuse. An integrative water treatment module is proposed, combining multifunctional electrochemical reactors, aeration and sedimentation units, ion-exchange columns, automatic filtration systems, and intelligent non-contact water quality monitoring based on electromagnetic resonance spectroscopy. The technology offers reduced dependence on chemical reagents, minimal toxic waste generation, high operational flexibility, advanced automation, and cost-effective water regeneration. The study concludes that the integration of electrochemical, ion-exchange, and digital control technologies provides a promising foundation for sustainable and resource-efficient next-generation water treatment systems.

Keywords: *Water treatment; Water treatment at the water supply system inlet; Water treatment module; Comprehensive water treatment module; Electrochemical treatment of industrial wastewater for the removal of heavy metal ions and enabling the repeated reuse of treated water in an autonomous recirculation mode; Autonomous water treatment systems within the infrastructure of a smart mobile home and its structural equivalents; Technologies used in smart mobile home infrastructures capable of providing effective treatment of all types and classes of wastewater, including water that does not contain metals*

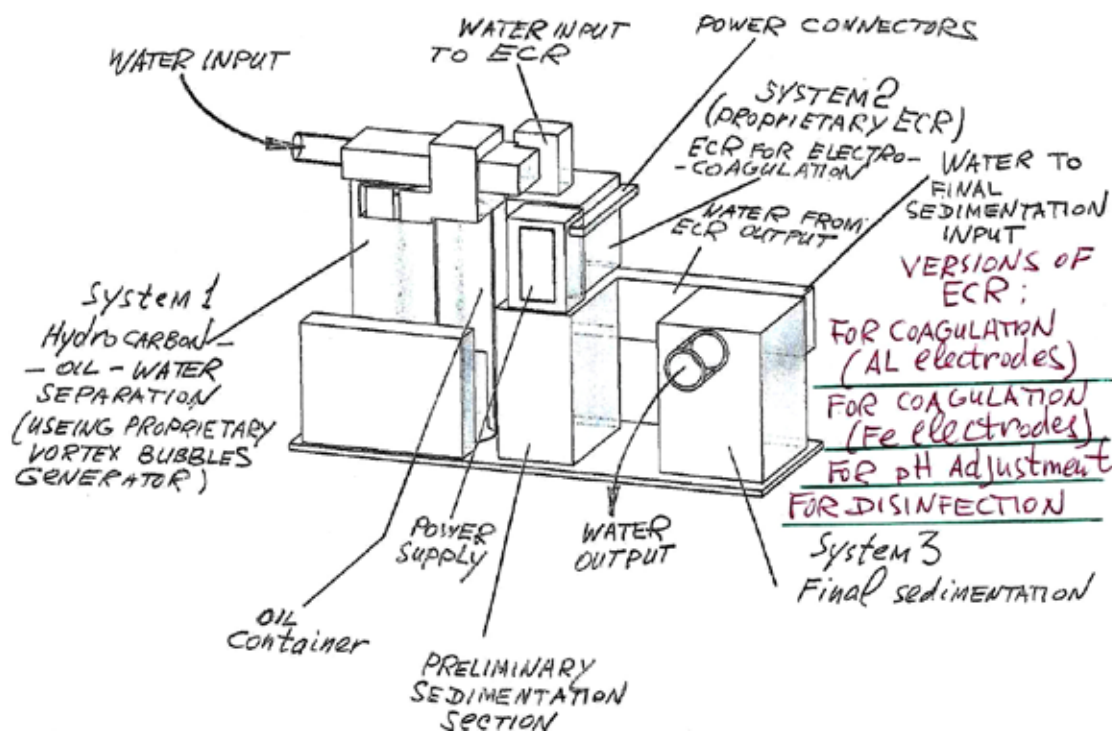
Approximately 16 different technological methods for the treatment of metal-containing wastewater are currently known.

The most widely used method is chemical reagent treatment. Under this method, caustic soda is added to the water, increasing its

alkalinity to a level at which metal hydroxides begin to precipitate.

Methods of artificial coagulation and flocculation can generally be disregarded, as their economic performance is highly unfavorable due to their high cost.

Figure 1.



The electrocoagulation method can compete with the aforementioned chemical reagent method in terms of both cost and efficiency. In recent years, particularly in high-technology industries, this method has gained considerable popularity. However, it is unable to comprehensively solve all existing water treatment challenges. Moreover, the transition from a reagent-based treatment system to an electrocoagulation system requires significant capital investment while still failing to address all fundamental issues.

None of the currently known methods fully solve the problem of water treatment for repeated reuse and, consequently, the need to reduce water consumption for technological processes.

At present, electrocoagulation technologies represent the most advanced approaches for the treatment of metal-containing industrial wastewater. Despite their significant advantages over older chemical reagent methods, electrocoagulation technologies do

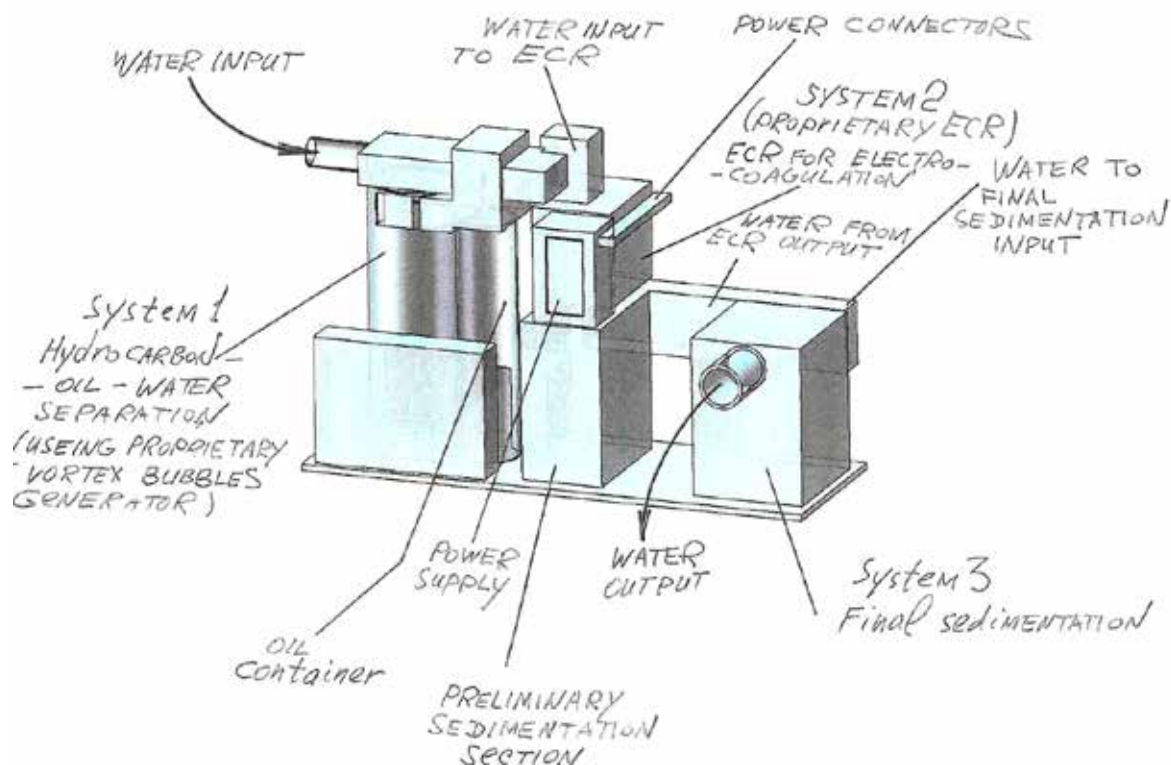
not resolve all critical issues associated with water treatment processes and possess several substantial limitations that are addressed by the integrated water treatment technology developed for the infrastructure of a smart mobile home.

The fundamental advantages of the proposed technology include: the elimination of the need for sedimentation processes; the absence of toxic waste requiring complex and costly disposal methods; insensitivity of the treatment process to the acidity level of the water being processed and, consequently, the absence of any need for pH adjustment; the versatility of the electrochemical reactor modules, allowing inexpensive and straightforward modification and customization for specific customer requirements while preserving the core technological and design principles; the possibility of extensive standardization and unification of smart mobile home water treatment modules; the capability of integration into virtually any

technological production line; the possibility of preliminary separation of electrically conductive and non-conductive components of aqueous solutions; and the possibility of

using natural, including biological, ion-exchange materials alongside electrochemical metal extraction from water.

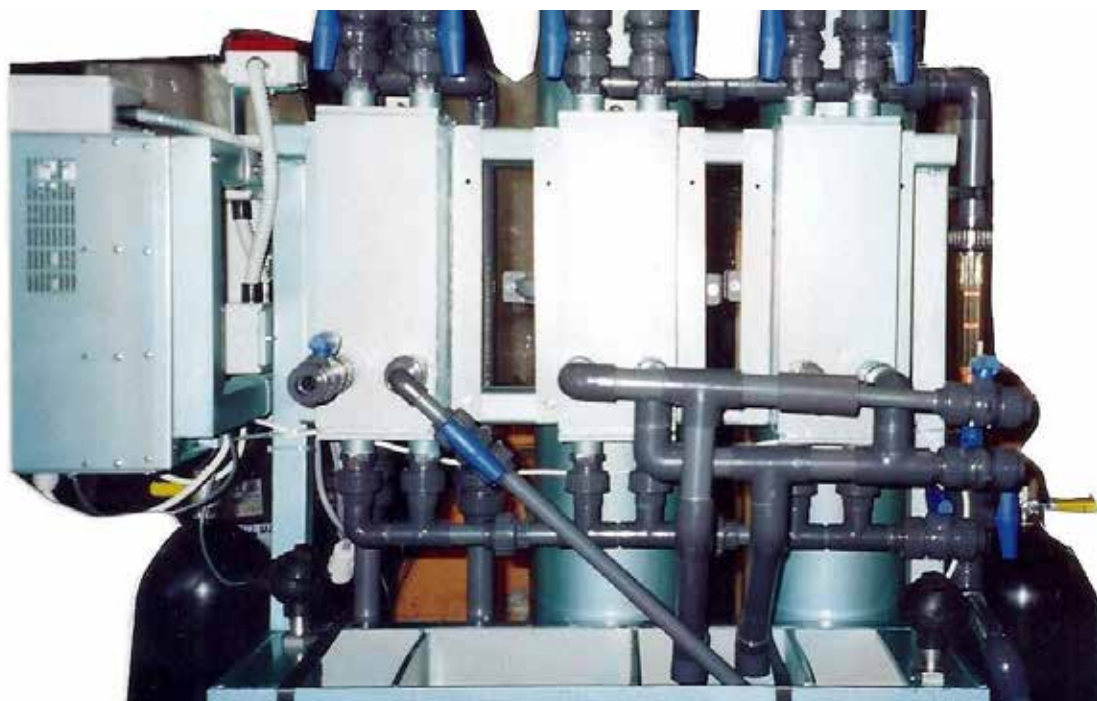
Figure 2.



The economic advantages of the water treatment technology developed for the in-

frastructure of a smart mobile home should also be considered separately.

Figure 3.

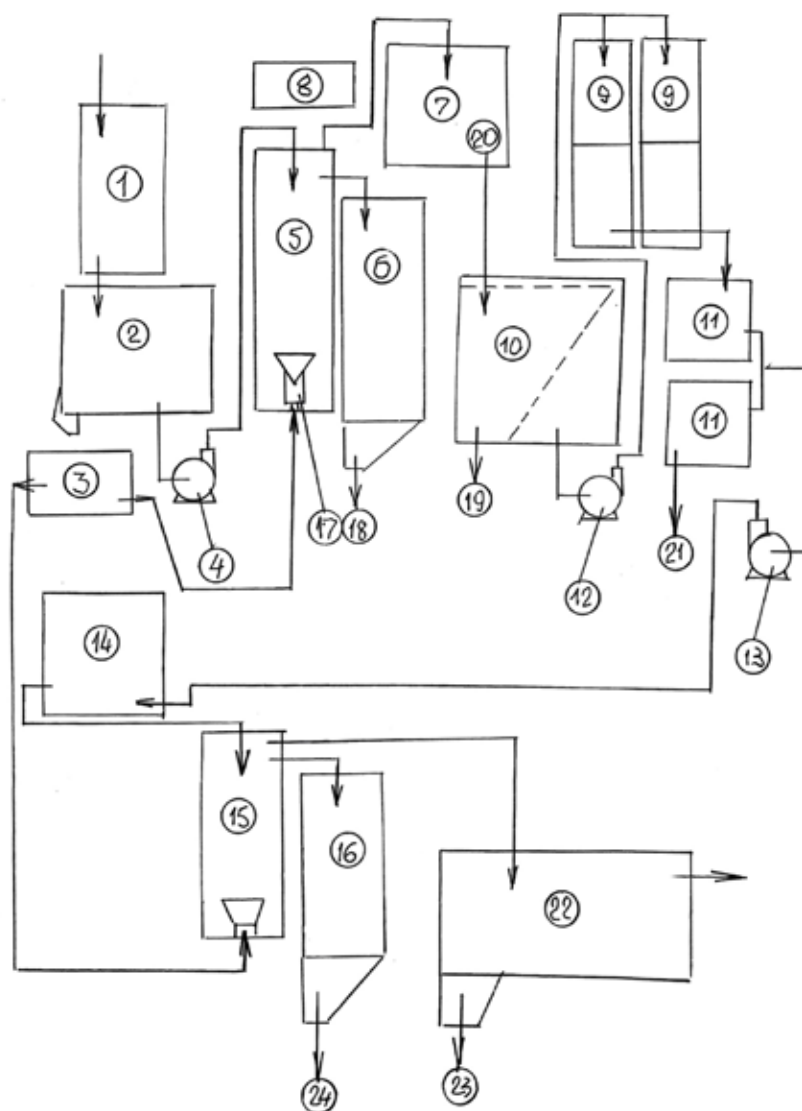


The vast majority of technologies currently used in water treatment and purification processes rely on chemical reagents. The market niche for technologies that operate without chemical reagents is virtually unoccupied. An even less developed niche is that of treatment technologies that do not generate difficult-to-dispose-of waste products. At present, such technologies are practically absent from the market. The seven technological modules that form part of the smart mobile home water treatment infrastructure, together with their various modifications and configuration options, provide a basis for occupying market sectors related to comprehensive water purification, regeneration, and the repeated reuse of water resources.

As of today, no technologies have been identified that enable the regeneration and repeated

reuse of industrial wastewater with minimal, economically acceptable costs while generating little to no toxic waste. Furthermore, the technical characteristics of the modules within the smart mobile home water treatment system allow them to be integrated into existing installations and production lines that utilize chemical and other treatment technologies. In such applications, the modules originating from the smart mobile home infrastructure solve specific local process challenges while simultaneously enhancing the overall technical performance of the existing systems due to their advanced technological capabilities. As a result, market entry for smart mobile home water treatment technologies within this category is significantly facilitated.

Figure 4.



Layout of operating modules within the integrative comprehensive water treatment module at the water supply system inlet.

The integrative comprehensive module is designed to treat groundwater and water resources of comparable quality to meet applicable water quality standards.

The capacity of the integrative comprehensive module ranges from 1,500 to 3,000 gallons per day.

The system consists of a series of sequential water monitoring and treatment units.

The treatment and monitoring process begins with a collection tank that receives all incoming water. Within this tank, comprehensive active monitoring of all key water quality parameters is performed using principles of electromagnetic resonance spectroscopy.

The water then enters a basin whose primary function is initial sedimentation and separation of the water stream into a fraction containing contaminants and sediment, and a fraction that has undergone gravitational sedimentation. The latter is pumped into a primary aeration column, where oxygen is dissolved into the water to the maximum possible extent through the action of an aerodynamic vortex foam generator connected to a compressor.

Upon completion of the first aeration and oxygen dissolution stage, a portion of the water containing foamed sediment is removed, while the remaining portion is directed to an electrochemical reactor operating under a multifunctional treatment cycle and equipped with electrochemical cells utilizing water-permeable carbon-carbon electrodes.

From the electrochemical reactor, the treated water is directed to a sedimentation basin, where it is divided into two streams. One stream is discharged for disposal after sediment separation, while the second, purified stream – processed through the combined multifunctional operating cycle of the reactor's electrochemical cells and the contact grid of the sedimentation basin – is directed to ion-exchange treatment columns.

Following treatment in the ion-exchange columns, the purified water is passed through automatic self-cleaning filters. After sediment removal within the filters, the water is directed to a second electrochemical reactor

operating under a multifunctional treatment cycle. This reactor can be configured to perform several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

The water treated in this manner is then directed to aeration columns, where oxygen is forcibly dissolved until full saturation is achieved. At the outlet of these columns, sediment and other foamed contaminants are separated from the main water flow and disposed of, while the remaining purified water is directed through a storage reservoir for delivery to end users.

The diagram designates the following components:

1 – A tank into which water enters from the supply system or collection manifold. This tank contains active online monitoring systems for detecting contaminants in the water based on the principles of electromagnetic resonance spectroscopy (an invention of the project authors).

2 – A primary sedimentation basin connected to Pump 4 and equipped with a sludge discharge line.

3 – A compressor connected to aerodynamic foam generators installed in the columns for the separation of sediment fractions and other contaminants.

4 – A centrifugal pump with all necessary supporting infrastructure.

5 – A column for aeration and oxygen dissolution in water, as well as for lifting foamed contaminants and organic matter to the upper section of the column.

6 – A column for separating foamed sediment and contaminants from the water mass.

7 – An electrochemical reactor with a multifunctional operating cycle. The reactor can be configured for several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

8 – A non-contact water quality monitoring system controlled by a dedicated processor connected to sensor modules installed at designated sections of the pipeline network and operating on the principles of electromagnetic resonance spectroscopy.

9 – Sectional ion-exchange treatment columns. Depending on the required processing capacity, a column may contain one, two, or three sections. This structure allows a single column to incorporate up to three ion-exchange materials, including natural ion-exchange media such as zeolite.

10 – A sedimentation basin receiving the discharge from the electrochemical reactor. Water separated from sediment in this basin is pumped to the inlet of the ion-exchange treatment columns (9).

11 – Automatic self-cleaning mechanical filters, which may be replaced by automatic membrane filters.

12 – A pump supplying purified water from sedimentation basin 10 to the ion-exchange treatment columns 9.

13 – A pump supplying purified and filtered water from filters 11 to the second electrochemical reactor operating under a multifunctional treatment cycle.

14 – An electrochemical reactor with a multifunctional operating cycle. The reactor can be configured for several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

15 – A column for aeration and oxygen dissolution in water and for lifting foamed contaminants and organic matter to the upper section of the column. An aerodynamic vortex foam generator is installed in the lower section of the column.

16 – A column for separating foamed sediment and contaminants from the water mass.

17 – An innovative aerodynamic vortex foam generator, the inlet of which is connected to the compressor outlet.

18 – The outlet and discharge line from Column 6, which functions as a column for separating foamed sediment and contaminants from the water mass.

19 – A sludge discharge line for removing sediment from sedimentation basin 10.

20 – A pipeline conveying water treated in the electrochemical reactor to sedimentation basin 10. Water within the electrochemical reactor may undergo several treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

21 – A backup sludge discharge line from the automatic mechanical filters or their equivalents – membrane filters.

22 – A final storage tank for treated water prior to distribution for consumption.

23 – A backup discharge line for removing accumulated sediment and contaminants from the storage tank.

24 – A discharge outlet from Column 16, which is used for separating foamed sediment and contaminants from the water mass.

In the described configuration, all incorporated modules are multifunctional and can be adjusted to operate with several types of source water supplied to the inlet of the integrative comprehensive treatment module.

For the control and management of the electrochemical reactors, the integrative comprehensive module incorporates a control and monitoring system functionally connected to non-contact electromagnetic resonance sensor modules operating on the principles of electromagnetic resonance spectroscopy.

The system is capable of operating in a fully autonomous automatic mode, providing complete control over treatment results and water quality at every stage of the treatment process.

The system offers complete operational flexibility and, during operation and configuration, can modify both the sequence and specific characteristics of the treatment process according to operational requirements and the technical parameters of the integrated components and subsystems.

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submitted 30.05.2026;

accepted for publication 14.05.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-159-164



PROCESSING OF RADIOACTIVE WATER. (Purification of water from radioactive isotopes and heavy metal ions using biomass derived from algae)

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Cite: Korobko M. (2026). *Processing of Radioactive Water. (Purification of water from radioactive isotopes and heavy metal ions using biomass derived from algae).* Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-159-164>

Abstract

The article examines a technology for the purification of water contaminated with radioactive isotopes and heavy metal ions using biomass derived from dried and granulated marine algae. Particular attention is given to the ion-exchange properties of the biomass, which enable the effective removal of radioactive ions and heavy metals without the use of chemical reagents. The design features of modular purification systems equipped with disposable ion-exchange cartridges and methods for the disposal of spent materials are also described. Special attention is devoted to innovative non-contact monitoring systems based on resonance sensors capable of continuously and selectively measuring the concentrations of various components in water and aqueous solutions under radioactive conditions. The article presents the operating principles of the proposed sensor technology, calibration methods, and the application of resonance-based monitoring for real-time water quality control. In addition, economic aspects of the technology are analyzed, including the potential market for purification and monitoring equipment in the nuclear power industry. It is concluded that the proposed combination of ion-exchange purification and advanced resonance monitoring technologies offers significant potential for improving the efficiency, safety, and environmental sustainability of radioactive water treatment processes.

Keywords: Heavy metal ions; Radioactive isotopes; Biomass derived from marine algae; Granulated dried algae; Radioactive isotope ions; Potential for ion-exchange reactions; Ion-exchange reactions for the adsorption of radioactive isotope ions

**Purification of water from
radioactive isotopes and heavy
metal ions using biomass
derived from marine algae**

1. Ion-Exchange Nature of Purification.

Practical experience has demonstrated that dried biomass of algae of the OZOLA type possesses ion-exchange properties that enable the adsorption of heavy metal ions and radioactive isotope ions.

For purification, the contaminated water is passed through a volume of biomass where, during the contact period, ion-exchange processes occur, resulting in the absorption of radioactive metal isotope ions and associated heavy metal ions by the biomass.

Figure 1.



Figure 2.



Tests and industrial operation of water purification systems at nuclear reactor facilities have shown that the purification efficiency achieved using OZOLA biomass can reduce residual contaminant concentrations to as low as 0.000001 milligrams per liter, exceeding the requirements of current environmental standards.

2. Design of the Modular Purification system

The modular purification system consists of a single column or multiple columns, each assembled from standardized segments.

Typically, a column may contain one, two, or three segments connected by a special coupling manufactured from nylon and polyvinyl chloride and equipped with a silicone rubber seal. The connection or disconnection of segments requires no more than one minute per joint.

Each segment can accommodate up to three ion-exchange cartridges. Each cartridge consists of a knitted polyester sleeve filled with OZOLA biomass. The ion-exchange cartridges are designed for single-use operation.

The knitted polyester sleeves are mass-produced, and their cost does not exceed 5 US dollars per unit.

The columns and associated piping are assembled and installed on a dedicated support frame that includes pumps, self-cleaning mechanical filters, measuring instruments, and monitoring equipment.

The cost of a modular purification system with a capacity of 1 cubic meter per hour, including three columns with three segments each, one pump, a cascade of two mechanical inlet filters, and a cascade of two automatic mechanical outlet filters, is approximately 35,000 US dollars.

The cost of OZOLA biomass required for one ion-exchange cartridge is approximately 50 US dollars.

3. Disposal of Purification Waste

Spent ion-exchange cartridges can be disposed of using several methods.

The first option involves vacuum incineration, followed by encapsulation of the resulting ash within a specialized concrete mini-sarcophagus designed for long-term containment.

Figure 3.

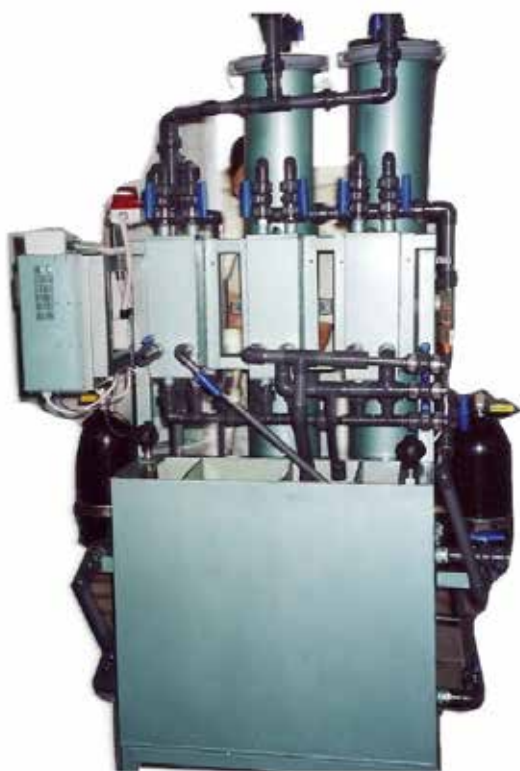


Figure 4.



The second option involves compressing the contaminated material into capsules, sealing them with lead-containing rubber, placing them into specialized storage drums, and storing them in decommissioned underground mine facilities.

4. Use of Module Housings for the Encapsulation of Spent material.

One disposal option involves the encapsulation of spent segments without disassembly or removal of the ion-exchange cartridges.

The encapsulated segments are subsequently transported and stored in decommissioned underground mine facilities.

5. Polyester Knitted fabric as a material for Ion-exchange Cartridges.

Polyester knitted fabric is manufactured in the form of a highly elastic tubular sleeve.

Such sleeves are mass-produced and can be supplied in any required quantities.

6. Problems arising in the monitoring of purification quality using existing technologies.

6.1. All existing technologies for monitoring the quality of water containing radioactive isotopes and radioactive materials

in combination with heavy metals require direct contact with water samples. Such methods present risks to both operators and equipment, since elevated radiation levels negatively affect the accuracy of measurement results.

6.2. Continuous real-time monitoring cannot be effectively implemented using existing technologies.

6.3. Monitoring instruments intended for operation in environments with elevated radiation backgrounds require specialized protective shielding, which increases their cost and reduces their reliability.

6.4. At present, there are no local rapid-monitoring technologies capable of providing the required measurement accuracy under such conditions.

6.5. The absence of real-time information regarding water quality prevents timely operational decision-making, which may lead to emergency situations involving unique and high-value industrial equipment.

7. Innovative nanometrology for operation in specialized equipment for the purification of water, other liquids, and aqueous solutions from radioactive isotopes.

8. Characteristics of the proposed application.

8.1. The proposed application consists of a resonance sensor equipped with a power supply unit, signal amplifier, signal converter, and a communication device for transmitting sensor data.

8.2. The sensor has a ring-shaped configuration and is installed on designated monitoring sections of the inlet and outlet pipelines of the water purification system.

8.3. The estimated cost of a sensor intended for water quality monitoring, including all associated peripheral equipment, is approximately 35,000 US dollars.

8.4. The estimated cost of a sensor designed for use in level measurement devices is approximately 1,450 US dollars.

Adaptation of the proposed instrument for measuring the concentrations of various components in water or aqueous solutions requires minimal time and effort.

Technologically, this process involves repeating the same calibration procedures based on determining the optimal resonance parameters characteristic of specific metal ions or chemical substances present in the solution. The calibration process takes into account the overall condition of the solution, the proportions between its components, and the chemical background of the medium, including the concentrations of components that remain relatively constant over long periods and do not significantly affect the measured parameters.

A methodology for calibrating the resonance circuit has already been developed and validated through prototype testing. The test results were positive and demonstrated the practical capability of modifying resonance circuit parameters as required under various operating modes, including fully automatic adjustment.

For the sequential measurement of different solution components, the signal generated by the sensor is continuously modified according to the optimal resonance parameters corresponding to each target component. As a result, the same instrument can measure the concentrations of multiple components sequentially, automatically adapting the resonance circuit to the resonance characteristics specific to each component.

All of these adaptive functions are incorporated into the instrument's control processors and have been successfully tested.

Figure 5.



9. Market size.

9.1. The estimated demand for water quality monitoring sensors used in nuclear reactors and nuclear power generation systems exceeds 15,000 units, since water purification systems typically have limited throughput and each installation requires at least two sensors.

9.2. The estimated value of these sensors is approximately 52.5 million US dollars. Installation, spare parts supply, and service support are estimated at 35% of the sensor value, corresponding to approximately 18.2 million US dollars annually.

9.3. Accordingly, the total projected market volume for the proposed monitoring application is estimated at approximately 70.7 million US dollars.

9.4. The estimated demand for level sensors intended for the same categories of facilities and industrial operations is approximately 50,000 units. The estimated market value of these level sensors is approximately 72.5 million US dollars.

9.5. The combined projected market volume for radioactive water quality monitoring sensors and level sensors designed for

operation in environments with elevated radiation backgrounds is estimated at approximately 143.2 million US dollars.

Selective monitoring of component concentrations in water and aqueous solutions

In simplified terms, the selective measurement and monitoring of concentrations of metal salts and other substances dissolved in water can be explained as follows.

Water possesses an unusually high dielectric constant, which is a consequence of the exceptionally large dipole moment of water molecules. As a result, the overall polarization response of a solution in an alternating electric field depends not only on the concentration of non-polar impurities but also on molecules whose dipole moments differ from that of water.

This difference forms the basis of the resonance method for selectively measuring impurity concentrations in water and aqueous solutions. When water is introduced into a resonant circuit, it establishes a characteristic resonance line specific to

water. Any impurity introduced into the water within the resonant circuit causes a shift in this resonance and in the corresponding resonance line.

Different impurities produce different resonance shifts depending on their concentration. A set of calibration relationships corresponding to specific metals or chemical elements makes it possible to selectively determine the magnitude of the resonance shift and, consequently, the concentration of each impurity present in the water or aqueous solution.

These calibration relationships are established through chemical calibration procedures using conventional analytical methods.

For solutions and liquids that are not water-based, the methodology and principles of selective concentration measurement are similar. The primary difference is that the reference component used for comparison is selected from among the constituents of the solution or liquid and is typically the component whose molecules possess the highest dipole moment within that particular medium.

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submitted 29.05.2026;
accepted for publication 13.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-165-170



STATIC PROPAGATION MODEL LIMITATIONS AS A ROOT CAUSE OF COVERAGE PLANNING FAILURES IN DENSE URBAN 5G DEPLOYMENTS

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Cite: Kozak A. A. (2026). *Static Propagation Model Limitations as a Root Cause of Coverage Planning Failures in Dense Urban 5G Deployments*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-165-170>

Abstract

Empirical path-loss models such as Okumura-Hata, calibrated for frequencies below 1500 MHz and base station heights above rooftop level, introduce systematic prediction biases exceeding 9 dB when applied to sub-6 GHz and millimeter-wave small cell deployments in dense urban environments. These biases propagate through the planning pipeline and produce site count overestimates of 65–80% relative to measurement-informed baselines. This paper presents a transfer-adaptive neural framework for 5G coverage planning that combines geospatially conditioned probabilistic propagation prediction, Pareto-weighted joint coverage-capacity deficit optimization, and closed-loop online adaptation with spatially varying regularization proportional to local measurement uncertainty. The framework was evaluated over a 180 km² urban region at 3.5 GHz using drive-test data from 800 km of road segments. Region-specific fine-tuning reduced mean absolute prediction error from 9.1 dB to 5.5 dB and decreased the required site count by 11–13% relative to non-adapted baselines, while compressing the planning cycle from 40–58 days to 14–22 days.

Keywords: 5G network planning; propagation path loss model; transfer learning; neural network; millimeter-wave; small cell deployment; multi-objective optimization; online model adaptation; coverage prediction; urban environment

Introduction

Planning tools used by most mobile network operators still rely on empirical path-loss models whose parametric forms were derived from measurement campaigns conducted in the 1960s and 1970s, when the environments being modeled bore little resemblance to the morphologically complex urban fabric of contemporary cities. The Okumura-Hata model (Hata, 1980), which remains the

functional backbone of many commercial planning tools, was calibrated for frequencies between 150 and 1500 MHz over distances of 1 to 20 km, with base station antenna heights substantially above rooftop level, conditions that are systematically violated in sub-6 GHz and millimeter-wave small cell deployments characteristic of 5G densification. The consequence is a systematic miscalculation of coverage radii, link budgets, and site counts

that propagates through the entire planning pipeline and ultimately manifests as persistent coverage holes, capacity bottlenecks, and expensive post-deployment correction campaigns.

Literature Review

The history of propagation modeling for cellular planning divides into three phases that differ in their epistemological approach rather than merely in their vintage. The first phase produced models grounded in statistical regression over measurement datasets collected in specific cities under specific antenna configurations. Hata's formulation (Hata, 1980) expresses path loss as a linear function of the logarithm of distance and frequency- and height-dependent correction terms derived from Okumura's Tokyo measurements. Computational simplicity made it the standard for decades, but the model's dependence on the particular morphological statistics of Tokyo in the late 1960s was largely ignored in practice: applying it to environments with different building height distributions, street layouts, or terrain profiles introduces biases that its own parameters cannot absorb. The second modeling phase introduced geometry-based stochastic channel models that treat propagation clusters statistically while preserving scenario-level physical plausibility. The 3GPP TR 38.901 framework (3rd Generation Partnership Project, 2017) provides stochastic models for urban macrocell, urban microcell, and indoor scenarios up to 100 GHz, parameterized from an extensive synthesis of measurement campaigns. The stochastic cluster structure captures the statistical distribution of path loss and delay spread across a population of links in a given scenario class, but it does not predict the signal level at a specific geographic point given a specific building configuration. The gap between stochastic scenario models and site-specific predictions is precisely where static planning tools fail most visibly in dense deployments, because the error variance of a stochastic model applied deterministically can exceed 10 dB in environments with strong local geometry effects (Sun et al., 2016a).

The third phase applies machine learning to propagation prediction, motivated by

the availability of geospatial data (building footprints, heights, land-use classifications, terrain elevation) that encodes the local propagation environment at a resolution that deterministic and stochastic models exploit only coarsely. Wang et al. (2018) survey the resulting model landscape and identify spatial non-stationarity, massive MIMO array effects, and dynamic blockage as phenomena handled inadequately by existing static frameworks. The transfer-adaptive framework developed here addresses the accuracy-scalability trade-off by learning environment-specific corrections from measurement data.

Method

The framework consists of three coupled components: a transfer-adaptive neural propagation model, a demand-weighted multi-objective coverage deficit optimization, and a closed-loop model adaptation mechanism driven by deployed-network performance feedback. The propagation model accepts a multi-channel geospatial grid in which channels encode terrain elevation normalized to a common geodetic datum, building height, building footprint density, land-use class as a categorical embedding, and frequency-specific free-space path loss computed analytically from the transmitter-receiver geometry. A neural network with three to six layers processes this grid to produce intermediate feature maps capturing spatially structured propagation environment characteristics at multiple scales; depth and filter count are selected based on cross-validated prediction error on a held-out regional dataset. A second network stage receives these feature maps together with a base station configuration vector (comprising antenna height, tilt angle, azimuth, transmit power, and carrier frequency) and outputs, for each grid cell, the mean and variance of a Gaussian distribution over the received signal metric.

Training proceeds in three stages whose boundaries correspond to distinct sources of inductive information. An initial stage uses geospatial and measurement data from multiple reference regions to learn a transferable prior; stochastic gradient descent with batch normalization and dropout regularization is applied throughout. A region-specific

fine-tuning stage adapts the model to the target deployment region using locally collected drive-test or crowdsourced signal measurements, with a reduced learning rate and an L2 regularization term anchored to the initial training weights to prevent catastrophic forgetting of general propagation relationships. The online adaptation stage uses streaming performance data from deployed sites with a spatially varying regularization coefficient $\lambda(x)$ that increases with per-cell measurement uncertainty, formalized as

$$\lambda(x) = \lambda_0 \times \sigma_{means}^2(x) / \sigma_0^2$$

where λ_0 and σ_0^2 are reference values set during fine-tuning and $\sigma_{means}^2(x)$ is the empirical measurement variance at cell x over a sliding observation window. This formulation ensures aggressive adaptation where measurements are dense and informative, and near-prior behavior where measurement coverage is sparse.

The site placement problem is formulated as a multi-objective constrained optimization over a demand-weighted aggregate deficit. At each grid cell i , the coverage deficit is

$$d_{cov}(i) = \max(0, p_{target} - \hat{p}(i))$$

where p_{target} is the operator-specified coverage probability threshold and $\hat{p}(i)$ is the predicted coverage probability derived from the model output distribution. The capacity deficit is

$$d_{cap}(i) = \max(0, L(i) / C(i) - 1)$$

where $L(i)$ is the demand-surface load estimate and $C(i)$ is the predicted sector capacity under the current configuration. These deficit types carry different functional forms and are normalized to a common scale before combination. The aggregate objective is

$$J = \sum_i w(i) \times [\alpha \times d_{cov}(i) + (1 - \alpha) \times d_{cap}(i)]$$

where $w(i)$ is the demand weight from the temporally resolved demand map and $\alpha \in [0, 1]$ is the Pareto weight.

A greedy sequential algorithm minimizes J by iteratively selecting the candidate site that provides the largest marginal reduction in the aggregate deficit, with interference contributions from already-selected candidates incorporated into signal quality predictions at each step. This interference-aware

update prevents the algorithm from selecting spatially clustered candidates whose aggregate interference would degrade coverage in adjacent zones, a failure mode of naive greedy selection that becomes significant at the inter-site distances characteristic of dense 5G deployments.

Results

Quantitative evaluation was conducted across three morphologically distinct sub-regions of an approximately 180 km² dense urban area at 3.5 GHz, using a 5 m grid resolution and drive-test measurements collected along 800 km of road segments. The non-adapted baseline, instantiated from the multi-region training corpus without fine-tuning, produced mean absolute prediction errors of 8.4 dB, 11.2 dB, and 7.1 dB in the residential, central business district, and transportation hub sub-regions respectively. Following region-specific fine-tuning, errors fell to 5.1 dB, 5.6–6.8 dB, and 5.3 dB. The central business district yielded the largest absolute reduction of 4.4–5.6 dB. The transportation hub yielded the smallest improvement at 1.8 dB, attributable to the limited penetration of the drive-test campaign into underground station environments, where reinforced concrete attenuates signals by 15–25 dB beyond values predictable from the surface geospatial representation. Aggregate site count reductions of 11–13% relative to the non-adapted baseline were confirmed across the full region, with the central business district contributing disproportionately because it carries the highest demand weights in the deficit map.

Held-out prediction error in the central business district exhibited a pronounced U-shaped dependence on λ . At $\lambda = 10^{-4}$ the error increased to 7.9 dB, indicating overfitting to the 88% training fraction; at $\lambda = 10^0$ it rose to 7.3 dB, indicating that the regularization term suppressed adaptation to region-specific features. The minimum held-out error of 5.6 dB was stable across approximately 5×10^{-3} to 2×10^{-2} . In the rural deployment scenario – where measurement density was roughly one-eighth of the urban value – the optimal λ shifted to 4×10^{-2} . Applying the urban-calibrated $\lambda = 10^{-2}$ in the rural scenario increased prediction error by 1.4 dB,

translating to a coverage radius overestimate of 600–900 m at 700 MHz and a site count underestimate of 8–12 sites across the 2,000 km² rural region. The factor-of-four shift in optimal λ between contexts establishes that a single globally calibrated coefficient cannot serve both deployment environments without incurring a meaningful accuracy penalty in one.

A sweep of the Pareto weight α from 0.0 (capacity-only) to 1.0 (coverage-only) was conducted for a suburban densification scenario involving 47 existing macro sites across a 500 km² region at 3.5 GHz. At $\alpha = 1.0$, 38 small cell candidates were selected in coverage-deficient areas, reducing the coverage deficit by 91% but leaving 14 high-demand commercial corridor cells with throughput-normalized load ratios exceeding 1.8 times the sector capacity limit. At $\alpha = 0.0$, 38 candidates were selected in high-demand commercial zones, reducing peak load ratio to 1.1 but leaving 23% of the coverage-deficient area unaddressed. The balanced setting $\alpha = 0.55$ achieved a 74% reduction in coverage deficit and reduced peak load ratio from 2.3 to 1.3, requiring 41 small cell sites rather than 38. No feasible 38-site configuration simultaneously achieved the 74% coverage deficit reduction and the 1.3 peak load ratio obtained with 41 sites. The 7.9% cost premium of the balanced solution reflects the geometric non-alignment of coverage and capacity deficit distributions in this deployment geometry and constitutes the irreducible planning cost of addressing both objectives jointly. Following initial deployment of the first tranche of macro sites in the central business district sub-region, the online adaptation stage was monitored over a 21-day window using streaming measurements from 31 deployed sectors. Prediction error decreased from 6.8 dB at day 0 to 5.1 dB by day 7, with diminishing returns thereafter, reaching 4.9 dB at day 21, a further reduction of only 0.2 dB over the final 14 days. Rapid initial convergence is attributable to the correction of systematic biases associated with building geometries absent from the municipal geographic information system: structures completed after the most recent map update. The residual error floor of approximately 4.9 dB is consistent with

the irreducible small-scale fading variance at 3.5 Hz in a rich-multipath environment, which contributes 3–5 dB of inherent variability to instantaneous signal level measurements that no large-scale propagation model can remove regardless of adaptation depth. In the underground transportation hub, where measurement feedback was limited to six street-level sectors adjacent to station entrances, prediction error within the tunnel geometry itself did not converge during the 21-day window, remaining at 14.3 dB at day 21, a 2.5 $\times$ larger residual than in the outdoor sub-regions.

Discussion

The 4.4–5.6 dB prediction error reduction in the central business district is not fully explained by global offset recalibration, which would shift errors uniformly rather than producing the sub-region-specific pattern observed. The non-line-of-sight path-loss deviation from simple power-law behavior documented by Akdeniz et al. (2014) at 28 GHz in Manhattan’s urban canyon geometry suggested a structurally similar magnitude of model discrepancy, and the convolutional feature extraction stage learns to represent the specific building-height variance and street-grid orientation patterns that drive this deviation locally. A parametric model could approximate this only through case-specific re-derivation of its exponent terms, a process that requires expert judgment and is not reproducible across regions without repeating the measurement campaign. The residential sub-region, with more uniform building stock and denser measurement coverage, shows a smaller but more consistent 3.3 dB improvement, the pattern one would expect if prediction error scales with morphological complexity and adaptation gain scales with measurement informativeness.

The regularization sensitivity finding has implications that extend beyond hyperparameter selection. Sun et al. (2016b) established that parameter stability across frequencies and distances is a quality criterion for path-loss models, arguing that physically motivated parametric structures generalize more reliably than fitted floating-intercept formulations. The equivalent criterion in the adaptive framework is the stability of

the optimal λ across measurement regimes. The factor-of-four shift between dense urban ($\lambda = 10^{-2}$) and sparse rural (4×10^{-2}) optimal coefficients implies that a single globally calibrated value would produce a 1.4 dB error penalty in the rural scenario. In rural deployments where terrain prominences provide coverage radii of 8–15 km at 700 MHz, a 600–900 m radius overestimate translates directly to gaps in road corridor coverage that only become visible after deployment, an outcome far more costly to correct than the marginal computational expense of computing a spatially varying coefficient. The inverse-uncertainty mapping for λ is therefore a necessary operational component of the framework.

The 7.9% site count premium for joint coverage-capacity optimization warrants examination of what the alternatives actually cost operationally. Wang et al. (2018) observe that 5G channel models developed for coverage evaluation are not applicable to capacity planning because spatial clustering of user demand introduces interference patterns absent from propagation-only analyses. The three additional sites required by the balanced formulation exist precisely because the coverage-optimal and capacity-optimal candidate locations are spatially separated: no single site addresses both deficits simultaneously in the commercial corridor sub-region. Coverage-only planning leaves 14 high-demand cells with load ratios exceeding 1.8 times sector capacity; capacity-only planning leaves 23% of coverage-deficient area unserved.

The site count comparison with static-model-based planning tools, which required 410–460 sites under Okumura-Hata to meet the same threshold that the adapted framework met with 247–252, reflects error am-

plification across a sequential planning pipeline rather than a simple bias shift. The static planning tools' 40–58 day planning cycles are partly an artifact of the manual re-calibration iterations required when initial predictions diverge from post-deployment measurements, iterations that the closed-loop adaptation mechanism eliminates by construction, collapsing the cycle to 14–22 days.

Conclusion

The dominant source of coverage planning failures in dense urban 5G deployments is the structural mismatch between the functional form of static empirical propagation models and the geometric reality of contemporary urban environments, a mismatch that compounds through the planning pipeline into site count overestimates of 65–80% relative to an adapted framework operating on the same coverage threshold. The transfer-adaptive framework introduced here reduces this error by learning environment-specific correction functions from geospatial and measurement data, fine-tuning to regional morphology, and updating online with spatially adaptive regularization calibrated to local measurement uncertainty. Aggregate prediction error reductions of 3.6 dB and site count reductions of 11–13% relative to non-adapted baselines were demonstrated across a 180 km² dense urban evaluation region, with the largest gains concentrated in the morphologically most complex sub-regions. The Pareto-weighted joint optimization of coverage and capacity deficits requires a 7.9% site count premium over single-objective formulations, quantifying the irreducible cost of addressing geometrically non-aligned deficit distributions in a single planning cycle.

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submitted 26.05.2026;
accepted for publication 02.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-171-178



NEUROADAPTIVE CLOSED-LOOP TRAINING IN AVIATION: A DUAL-STAGE fNIRS/EEG FRAMEWORK FOR REAL-TIME WORKLOAD REGULATION AND DIAGNOSTIC REMEDIATION

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Cite: Nicolas Jean Lejeune. (2026). Neuroadaptive Closed-Loop Training in Aviation: A Dual-Stage fNIRS/EEG Framework for Real-Time Workload Regulation and Diagnostic Remediation. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-171-178>

Abstract

Cognitive factors account for approximately 26% of civilian aviation incidents, yet simulator-based training programs operate without real-time measurement of trainee cognitive state. This article introduces a dual-stage neuroadaptive closed-loop training framework in which a within-session fNIRS/EEG workload controller and a session-level LSTM diagnostic classifier are coupled through a rolling per-subject workload envelope re-estimation procedure. The online stage fuses anterior prefrontal HbO₂ concentration with frontal theta power density to modulate scenario complexity continuously; the offline stage segments completed sessions by flight phase and identifies recurring performance deficiency patterns to construct individualized remediation paths for subsequent sessions. A 56-participant flight simulator study (four sessions, 24-hour inter-session intervals) showed a 33.3% reduction in sessions-to-competency relative to an iso-difficulty control, with single-trial workload classification accuracy of 76.4% under 16-channel low-motion conditions. The LSTM achieved an F1-score of 0.81 on phase-specific deficiency detection, outperforming a session-averaged logistic regression baseline by 53.5% on primary-phase identification rate.

Keywords: neuroadaptive training; closed-loop systems; fNIRS; EEG; mental workload; flight simulation; passive brain-computer interface; LSTM; cognitive load classification; aviation human factors

Introduction

Cognitive factors contribute to approximately 26% of civilian aviation incidents according to ICAO operational data (Aricò et al., 2016), and the training systems designed to address this failure rate share a structural defect: they assign scenario difficulty by elapsed flight hours and procedural check-

lists, not by whether the trainee's prefrontal executive resources are saturated, underloaded, or recovering from fatigue-driven capacity suppression. Borghini et al. (2014) documented that elevated frontal theta power and suppressed parietal alpha power are observable in pilots before performance metrics degrade, which means the intervention

window exists neurophysiologically and is invisible only to systems that wait for behavioral output before acting.

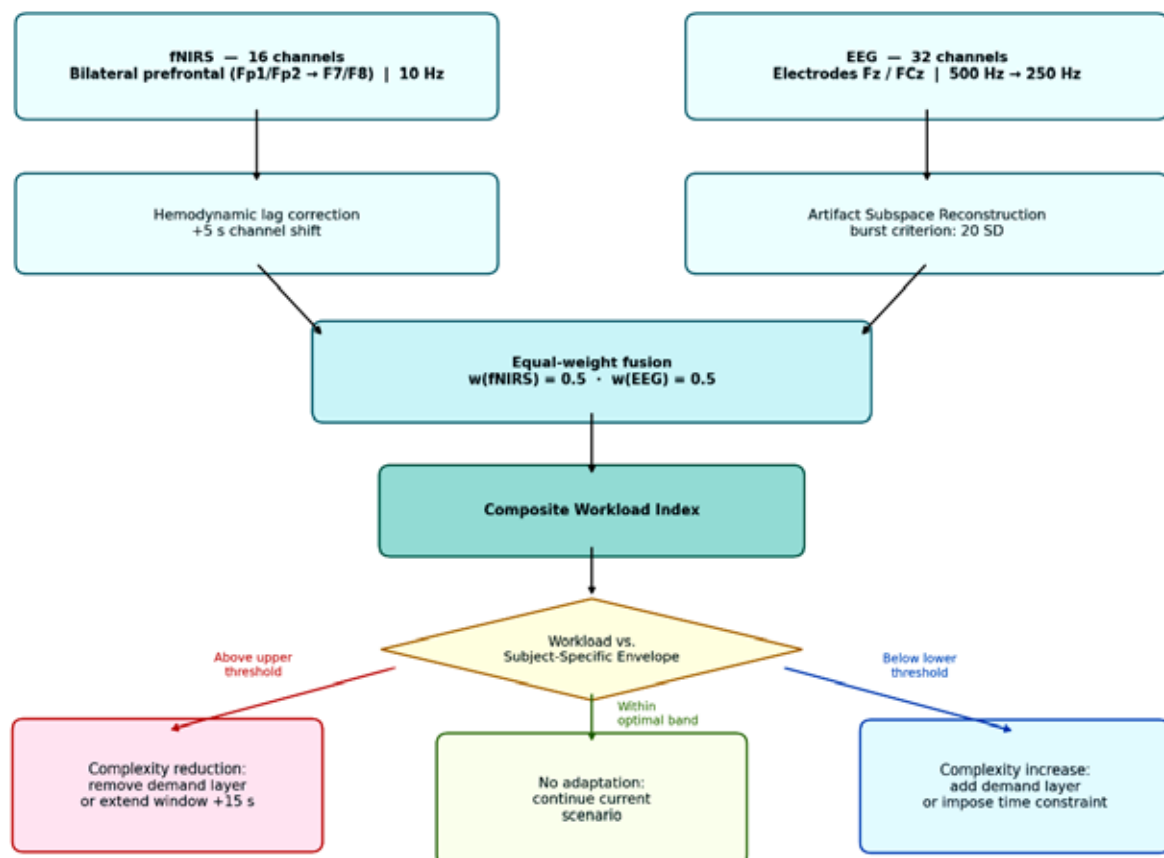
Literature Review

Parasuraman (2011) partially addressed the measurement gap between resource theory and operational sensing by mapping cognitive resource states onto neuroimaging correlates and establishing that prefrontal cortex activation indexed by fNIRS and frontal theta indexed by EEG track graded workload transitions, making a continuous control signal neurophysiologically available even when behavioral measures remain flat. Causse et al. (2017) operationalized this in a flight simulator by defining a neural efficiency index, the ratio of HbO₂ activation to task performance, that separates high-effort-low-performance from high-effort-high-performance states, providing the mechanistic basis for workload saturation detection. What none of these studies account for is the session-evolving character of the fNIRS-to-workload mapping: frontal theta power decreases across training sessions at constant task difficulty

as neural efficiency increases (van Weelden et al., 2022), which erodes the validity of any fixed workload threshold at a rate that is invisible to a system calibrated once at session 1 and never updated.

Passive BCI deployment in realistic aviation environments exposes a different but equally disqualifying limitation. Dehais et al. (2019) demonstrated group-level above-chance workload classification during actual flight using six dry EEG electrodes, but single-trial accuracy was reliable only under low head-displacement conditions, a constraint intrinsic to the problem because the flight phases carrying the highest workload demand are also the phases with the greatest head and body motion. Hinss et al. (2023) quantified cross-session classification drift in the COG-BCI dataset at an average of 9.3 percentage points without session-specific re-calibration, confirming that single-calibration BCI deployments accumulate classification error across sessions at a rate that would produce a monotonically increasing false-positive adaptation rate in any closed-loop system built on them.

Figure 1. Biometric Data Acquisition and Workload Index Computation Pipeline



Among adaptive training studies, Mark et al. (2022) is the closest precursor to the present work: fNIRS-informed neuroadaptive training in a four-session flight simulator produced significantly higher performance levels by session 4 relative to a non-adaptive control, with the neuroadaptive group reaching higher simulator complexity tiers. The adaptation mechanism, however, operated at session boundaries on cumulative fNIRS data, which means mid-session workload excursions, including the saturation events that Borghini et al. (2014) showed precede performance degradation by a detectable lag, passed without correction until the session had already concluded. Klaproth et al. (2020) integrated a passive BCI with an ACT-R cognitive model and achieved 87% accuracy in representing individual pilot responses to cockpit alerts, operating in classification-and-report mode, so the system diagnosed cognitive state without acting on the diagnosis within the session. Feltman et al. (2024) added a finding that the adaptive training literature has largely treated as noise: EEG workload manipulation effects are not uniform across individuals, and group-level threshold calibration systematically misclassifies the workload states of trainees at both extremes of the individual-differences distribution, a problem the present framework addresses through per-subject envelope estimation.

Method

The online adaptation stage receives a composite workload index computed by fusing anterior prefrontal HbO₂ concentration, updated every 5 seconds after hemodynamic lag correction via a 5-second shift of the fNIRS channel relative to the task event stream, with frontal theta power density computed at electrodes Fz and FCz at 250 ms resolution in the 4–8 Hz band. Equal modality weights (0.5/0.5) were selected based on the false-positive/missed-detection trade-off; this weighting is an empirically derived operating point. Crossing the subject-specific upper threshold triggers a complexity reduction: one concurrent task demand is removed, or the available response window is extended by 15 seconds. Crossing the lower threshold triggers a complexity increase: an additional demand layer is introduced, or

a time constraint is imposed. The subject-specific workload envelope is re-estimated after each session by jointly analysing the HbO₂ efficiency trajectory, the frontal theta trend across the session, and the session performance outcome, three signals that together distinguish genuine workload reduction from fatigue-driven HbO₂ suppression, the confound identified by Dehais et al. (2020) as the central interpretive challenge in longitudinal fNIRS deployment.

The offline diagnostic stage segments completed session time series by flight phase, covering takeoff, climb, cruise, descent, approach, and landing, and processes the resulting multimodal sequences through a two-layer stacked LSTM (64 units per layer, softmax output over six phase-specific deficiency classes). The LSTM output determines which flight phase receives targeted scenario emphasis in the subsequent session. A session-entry priming constraint prevents the online adaptation algorithm from reducing scenario complexity below the minimum diagnostic threshold during the designated remediation window, addressing the structural gap present when a trainee enters a session targeted at approach instability but has scenario complexity reduced by early-session fatigue detection before the targeted failure mode is presented at sufficient load.

The simulator environment was a PC-based flight simulator platform replicating a single-engine general aviation aircraft, instrumented with a 16-channel continuous-wave fNIRS device (10 Hz sampling, bilateral prefrontal coverage from Fp1/Fp2 to F7/F8 in the 10–20 system) and a 32-channel EEG amplifier (500 Hz, hardware-referenced to Cz, downsampled to 250 Hz for online processing). The 18 flight segments were structured around the competency units defined in ICAO Doc 9868 PANS-TRG: aircraft handling, instrument procedures, and crew resource management load was varied across difficulty tiers by manipulating traffic density, weather minima, and ATC instruction complexity. Artifact Subspace Reconstruction with a burst criterion of 20 standard deviations suppressed motion artifact from control inputs in the EEG stream. Fifty-six participants from a university flight training program were assigned to the neuroadaptive

condition ($n = 28$) or iso-difficulty control ($n = 28$) by stratified randomization on an initial 10-minute N-back calibration score, ensuring matched initial skill distributions across groups. Both groups completed four sessions of 60 minutes each at 24-hour inter-session intervals. The training scenario set comprised 18 flight segments across three difficulty tiers; the neuroadaptive condition accessed all tiers via the workload controller, and the control condition progressed through a fixed instructor-assessed sequence at session boundaries. The LSTM was pre-trained on 224 labeled session recordings from a prior cohort matched for aircraft type, simulator platform, and session duration, with instructor-assigned deficiency labels at inter-rater agreement $\kappa = 0.76$. The held-out test set comprised 112 session recordings from the 28 neuroadaptive-condition participants across all four sessions.

Results

Mean sessions-to-threshold was 3.4 ($SD = 0.6$) under the neuroadaptive condition and 5.1 ($SD = 0.9$) under the iso-difficulty control, tested across both groups on identical simulator platform, scenario library, debriefing protocol, and blinded performance scoring, a 33.3% reduction in sessions-to-threshold by the neuroadaptive condition measured by the sessions count metric defined in the Experimental Setup. The lower inter-individual variance in the neuroadaptive group ($SD = 0.6$ versus 0.9) is a functionally distinct outcome from accelerating average performance, reflecting the workload controller's equalizing effect across trainees at different initial skill levels, with direct implications for cohort certification timelines. The mechanism: bidirectional complexity modulation prevented the disengagement-driven performance regression observed in 11 of 28 control trainees during sessions 3 and 4, in which fixed difficulty fell below their growing competency ceiling and the workload index dropped into the sub-threshold disengagement zone for an average of 23 minutes per session, time during which the neuroadaptive controller would have introduced an additional demand layer or time constraint. Compressing inter-session intervals to 6 hours (secondary subgroup, $n = 8$, all other conditions iden-

tical) increased mean sessions-to-threshold under the neuroadaptive condition to 4.7 ($SD = 0.8$), because fatigue-driven HbO_2 decline persisted into the subsequent session and caused the workload controller to underestimate recovered capacity, producing systematic under-loading during the first 18 minutes of each compressed session.

Under the 16-channel, low-motion, per-subject-calibration condition defined in the Experimental Setup, single-trial fNIRS workload classification accuracy was 76.4% ($SD = 5.1\%$). Reducing the electrode configuration to 6 channels, tested on the same 28 subjects in counterbalanced order under identical simulator sessions and calibration procedures with electrode count and spatial coverage as the sole varying condition, dropped accuracy to 61.2% ($SD = 8.7\%$). The operational consequence is disproportionate to the accuracy drop: below 10 active prefrontal channels, false-positive overload detections reached 18.3% of adaptation events versus 6.1% under the 16-channel configuration, meaning that one in five complexity-reduction events was unjustified and the adaptation algorithm was net-counterproductive at that hardware specification. Under the high head-motion boundary condition (motion-platform simulator, roll rates up to $30^\circ/s$, $n = 12$), fNIRS signal quality degraded by 41% relative to the seated condition, the false-positive rate reached 31.2% per session, and inappropriate complexity reductions occurred in 4 of 12 trainees during the upset recovery phase, produced by motion-induced scalp blood flow redistribution generating HbO_2 fluctuations correlated with vestibular activation, which the short-separation noise regressor removed at only 66% efficiency.

On the 112-session held-out test set, the LSTM achieved phase-specific deficiency detection F1-score of 0.81 (precision = 0.79, recall = 0.83) and identified the primary deficiency phase in 74.1% of sessions. A session-averaged logistic regression baseline, trained on the same 224-session dataset, tested on the same held-out set with identical features and train/test split, identified the primary deficiency phase in 48.2% of sessions, a 53.5% relative disadvantage measured by correctly identified primary deficiency phases, attributable to the logistic regression's reduction

of flight-phase time series to scalar summary statistics that cannot encode the temporal dependency between workload escalation onset and subsequent control input degradation. Reducing the LSTM training set to 56 sessions under otherwise identical evaluation conditions dropped F1-score to 0.63 and primary-phase identification rate to 57.1%, eliminating the diagnostic advantage; 150 labeled session recordings constitute the minimum operational threshold for deployment of the diagnostic stage.

Parameter sensitivity of the workload envelope re-estimation interval, evaluated retrospectively across all 28 neuroadaptive-condition participants by simulating less frequent updates on the recorded session data, revealed that per-session re-estimation produced the observed 3.4 sessions-to-threshold, every-two-session re-estimation increased this to 3.9 due to a one-session adaptation lag, and fixed calibration with

no re-estimation yielded 4.6 ($p = 0.41$ versus iso-difficulty control, unpaired t-test, $n = 28$ per group), because the session-1 envelope underestimated optimal workload by an average of 31% by session 4. Performance degrades nonlinearly below 0.5 updates per session.

The composite index trade-off, evaluated under the primary 16-channel low-motion condition: EEG-only computation raised the false-positive rate to 14.7% but preserved 250 ms temporal resolution; fNIRS-only computation lowered the false-positive rate to 4.9% but missed 22.3% of workload spikes lasting fewer than 8 seconds. Equal fusion achieves a false-positive rate 57.5% below EEG-only and captures 94.1% of overload events detectable by EEG-only, at the cost of a 4–6 second detection latency for short spikes, a latency that falls within one task cycle for all 18 scenario types in the tested environment.

Table 1. Performance Outcomes Across Experimental Conditions and Classification Models

Parameter	Neuroadaptive (16-ch)	Iso-Difficulty Control	6-ch fNIRS	LSTM (n=224)	LR Baseline
Sessions-to-threshold (mean)	3.4	5.1	4.7*	—	—
Sessions-to-threshold (SD)	0.6	0.9	0.8	—	—
Workload classification accuracy	76.4%	—	61.2%	—	—
False-positive adaptation rate	6.1%	—	18.3%	—	—
Primary-deficiency phase ID rate	—	—	—	74.1%	48.2%
LSTM F1-score (held-out)	—	—	—	0.81	0.54
Min. training sessions for deployment	—	—	—	~150	~40

Discussion

Thirty-three percent faster time-to-competency relative to the iso-difficulty control is not, by itself, what distinguishes the present framework from prior neuroadaptive work. Mark et al. (2022) produced a directionally equivalent competency advantage in a four-session fNIRS training study. The mechanistic distinction is that the Mark et al. architecture adjusted difficulty at ses-

sion boundaries on cumulative neural data, which means the intra-session workload excursions documented here, with 11 of 28 control trainees spending an average of 23 minutes per session in the disengagement band during sessions 3 and 4, would have been unaddressed until the following session. The narrower inter-individual variance in the neuroadaptive group ($SD = 0.6$ versus 0.9 in the control) is the quantitative signature of

intra-session correction: trainees at the lower end of the initial skill distribution, who benefit most from downward complexity modulation during early-session saturation events, are the same trainees who drive variance in fixed-difficulty protocols, and the controller eliminated 33% of their excess session count relative to the mean. In the context of ab initio training programmes, where simulator hours represent the dominant cost driver and minimum hour requirements are regulatory floors, a one-third reduction in sessions-to-competency translates directly into fleet readiness timelines and per-trainee programme cost.

Contrary to Zander and Kothe (2011), who argued that passive BCI classification accuracy in the 70–80% range is sufficient for adaptive human-machine system deployment, 76.4% single-trial accuracy under the 16-channel, low-motion, per-subject-calibration condition generates a 6.1% false-positive adaptation rate that is operationally manageable, and the same accuracy level at 6-channel sparse configuration generates 18.3%, at which point the architecture is counterproductive. The Zander and Kothe sufficiency claim was derived for binary go/no-go systems where false positives add latency without reversing behavioral state. In a difficulty-modulation loop, a false-positive overload detection removes scenario challenge at the precise moment when cognitive load is within the productive band, so the cost function is asymmetric: a missed detection delays adaptation by one task cycle, and a false positive actively reduces scenario difficulty during the window when the trainee was closest to optimal load.

At 6-hour inter-session intervals, mean sessions-to-threshold in the neuroadaptive condition increased to 4.7, statistically indistinguishable from the iso-difficulty control value of 5.1 at the observed sample size. The rolling envelope re-estimation procedure cannot distinguish between a trainee whose prefrontal HbO₂ baseline has recovered and one in whom fatigue-driven hemodynamic suppression mimics a low-workload state, because both present as reduced HbO₂ relative to the prior session's endpoint.

The 53.5% relative advantage of the LSTM over the logistic regression baseline

on primary-phase deficiency identification (74.1% versus 48.2%, identical training and test conditions) confirms the sequential dependency structure documented by Klaproth et al. (2020): alert-processing failures in their EEG-integrated cognitive model were encoded in the timing relationship between workload onset and response degradation, not in any scalar feature of either variable alone. The minimum training threshold of 150 labeled session recordings before the LSTM contributes meaningfully to remediation path construction is a more operationally significant barrier than the 16-channel hardware requirement, because it is invisible at the system design stage and only becomes apparent after deployment at an operator without historical data infrastructure.

The motion-platform boundary condition (roll rates up to 30°/s, false-positive rate 31.2%, inappropriate complexity reductions in 4 of 12 trainees during the upset recovery phase) is the framework's most operationally consequential failure mode, and it is structurally paradoxical: UPRT is simultaneously the training context where workload monitoring would provide the greatest safety value, given the role of stress-induced attentional fixation and spatial disorientation in upset accidents documented by Callan et al. (2016), and the context where the primary sensing modality generates its highest artifact contamination.

Conclusion

Continuous within-session fNIRS/EEG workload control coupled to a cross-session LSTM diagnostic engine through rolling per-subject envelope re-estimation makes it operationally possible, for the first time in a multi-session aviation training context, to correct intra-session workload excursions before they produce behavioral consequences, a capability that reduces sessions-to-threshold by 33.3% under 24-hour inter-session intervals and whose mechanism, bidirectional complexity modulation preventing 23-minute disengagement episodes in 11 of 28 control trainees, would not be accessible to any system operating on session-level data. The specific question the present data cannot answer is whether a pre-session resting-state HbO₂ baseline reset eliminates the framework's 6-hour inter-session inter-

val constraint, the condition under which the architecture currently fails and the one most relevant to high-tempo military and recurrent airline training schedules where 24-hour recovery windows are operationally unavailable.

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submitted 02.06.2026;
accepted for publication 16.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-179-185



ECOSYSTEM OF OIL PAINT PREPARATION. (Preparation of oil paints for use and application in contemporary painting with psychological rehabilitation functions)

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Cite: Liakh M. (2026). *Ecosystem of oil paint preparation. (Preparation of oil paints for use and application in contemporary painting with psychological rehabilitation functions).* Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-179-185>

Abstract

The article discusses an innovative approach to the preparation of oil paints for the restoration of works of art based on dynamic vortex mixing technologies. The author proposes the use of specialized vortex generators that provide highly homogeneous mixing of pigment powders with oil-based solvents, increase the contact time between components, and enable the microencapsulation of pigment particles within a shell formed by an ultra-pure oil component. Particular attention is given to improving the stability, durability, and overall quality of the paint layer through the use of ultra-pure raw materials, including alpha-lecithin derived from chicken eggs and the natural preservative lysozyme.

The article describes the design and operating principles of a vortex mixing system, emphasizing its manufacturability, scalability, and suitability for use in restoration workshops. The proposed technology combines advanced component preparation, vortex mixing, and microencapsulation processes to create high-quality restoration paints with enhanced performance characteristics. It is argued that such an integrated approach can significantly improve the quality of restoration work and extend the preservation lifespan of restored artworks.

Keywords: *Paints; Oil paints; Oil paint mixing; Oil paint preparation; Preparation of oil paint components; Dynamic mixing; Vortex mixing; New materials; Stability and durability of oil paint*

Introduction:

The author of this publication, as a specialist in gemstone geology and an artist creating innovative artistic compositions, proposes considering the feasibility of an innovative transformation of the process used to manufacture highly homogeneous

oil paints, particularly for restoration work, where the quality and durability of the materials employed are of decisive importance.

As is known from the history of technology, all oil paints previously used by artists were produced from entirely natural

components, with chicken egg yolk serving as the oil medium.

Even today, it remains difficult to completely separate the yolk (egg oil) from the egg white (albumin).

Figure 1.



As a result, traces of albumin are almost always present in the egg oil, while traces of egg oil remain in the albumin.

This condition of the paint medium causes the paint to lose its uniformity and homogeneity relatively quickly.

When historical paint layers are examined under a microscope, destructive phenomena such as paint shrinkage, deformation, and cracking of the outer paint surface can be clearly observed.

Over time, these processes lead to the gradual deterioration of the paint layer and the loss of the artwork's original appearance.

During restoration work, it is naturally necessary to use paints whose composition and production methods are as close as possible to the original materials.

Even under modern conditions, this remains a difficult task.

In other words, if the objective is to use paints for restoration that possess chemical compositions and properties equivalent to the original materials, it becomes necessary to reproduce the manufacturing methods and technologies used in previous centuries, effectively returning the modern restoration process to the challenges associated with medieval oil paint production.

Both historically and today, the key challenge has been achieving the most complete possible separation of egg yolk oil from egg white albumin.

The issue of homogeneous mixing also remains important, but it is secondary be-

cause obtaining pure initial paint components largely determines the final quality of the paint in virtually all respects.

Therefore, in order to address all stages involved in the creation of a new type of oil paint for restoration applications through an innovative approach, an equally integrated and comprehensive solution is required for each material and technological operation involved in the overall process.

- The first issue is the production of pure or even ultra-pure egg oil.

- The second issue is the production of a natural preservative for the paint to ensure its stability and durability.

- The third issue is the reliable and rapid mixing of pigment powder with ultra-pure egg oil.

- The fourth issue is the encapsulation of pigment microparticles within a shell of ultra-pure egg oil.

- The fifth issue is the coating of the capsules produced during mixing, consisting of a pigment particle core and an ultra-pure egg oil shell, with a liquid natural preservative.

Assuming that the issues of obtaining ultra-pure egg oil and an equally pure natural preservative have been solved.

Mixing and encapsulation, which are technologically much more complex, require a detailed explanation.

There are technologies known as vortex mixing.

The implementation of such technologies requires special vortex generators, which are

joined along the axis in the quantity needed to ensure the specified production capacity.

In this generator, the pigment in the form of micropowder is placed in the central axial opening, while egg oil or its equivalent is supplied under pressure into an annular trapezoidal channel, from where it passes through peripheral axial channels into tangential channels and is then injected into the pigment.

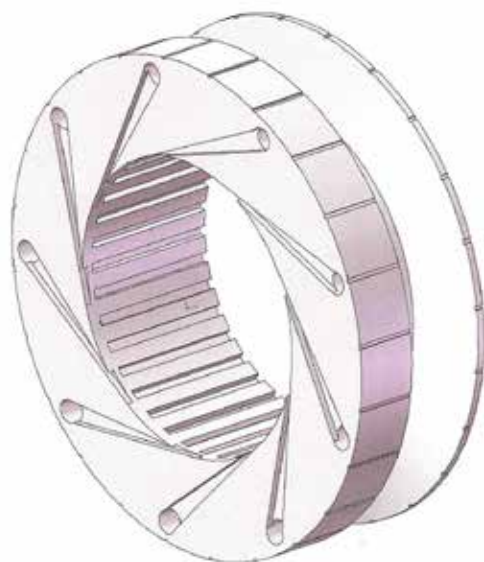
The tangential channels are designed so that the oil outlet openings range from 5 to 10 microns.

The dispersion of the sprayed oil also forms droplets ranging from 5 to 10 microns.

The topology of the tangential channels is designed and produced in such a way that the injection from each channel follows a spiral trajectory.

Since the number of such channels in a single generator may reach 15, this generator provides 15 spirals at the pigment inlet, whose injection transforms the pigment and spiral oil flows in the axial opening of the generator into a vortex tube, where microencapsulation takes place.

Figure 2.



There is another important factor arising from the properties of the vortex tube – the contact time between the oil and the pigment within such a tube increases by at least 3.5 times compared with conventional mechanical mixing, while the linear flow velocity of the mixture remains unchanged.

Vortex generators are relatively easy to manufacture and operate and can function with virtually any type of pump, which is particularly important for restoration applications.

The following sectional model illustrates these characteristics.

Generators of this type can be manufactured at any scale, which is also important for restoration work, where the required quantity of paint is extremely small while quality requirements remain exceptionally high.

The following three-dimensional models of various stages of paint preparation system assembly demonstrate the simplicity of the installation while maintaining full functionality.

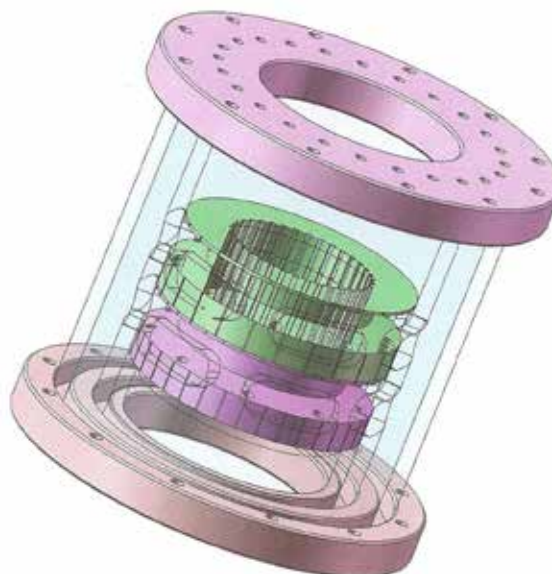
Such a system can be connected to any pump supplying the oil medium, simplifying its use at restoration sites of any type.

The diameter of such a vortex generator determines its productivity, making it possible to assume that, for local mixing of paint components in restoration work, a diameter not exceeding 35 mm would be sufficient.

The overall concept of this system is very simple and allows all components to be manufactured using basic geometric forms, which in turn enables operation by personnel without specialized production skills.

This design also contributes to low manufacturing costs, which is an important consideration when establishing a restoration facility.

Figure 3.

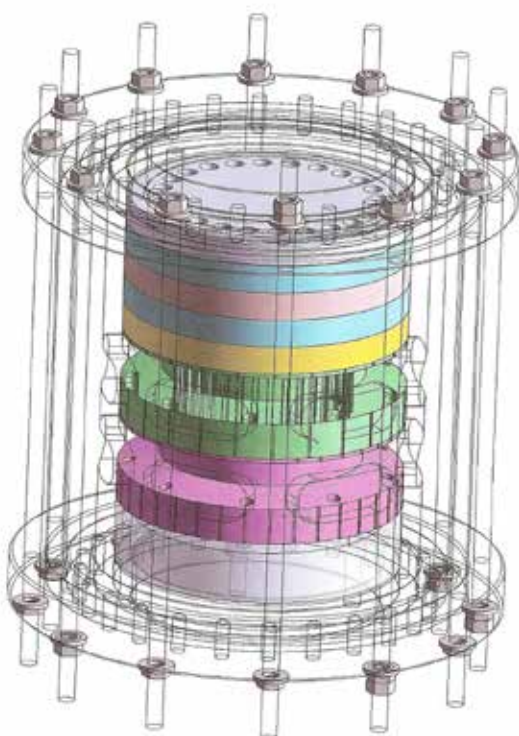


The author presents device models that demonstrate the simplicity and manufacturability of all components, as well as the ease of assembly and operation under restoration workshop conditions.

Figure 4.



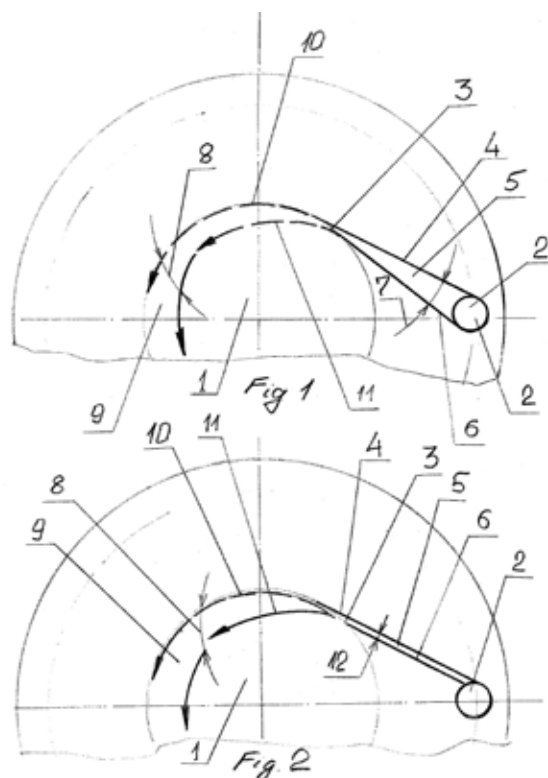
Figure 5.



As can be seen from the models, all housing components automatically center the vortex generators in contact with them, eliminating the need for numerous specialized parts and significantly reducing the cost of the system while maintaining the required level of paint preparation quality.

The assembly of the system is carried out using standard threaded rods, which further simplifies both the design and operation of the installation.

Figure 6.



The presented diagrams provide a detailed illustration of the dynamic mechanisms responsible for the formation of the vortex tube within the encapsulated paint preparation system.

As can be seen from the diagrams, the mechanisms involved in vortex tube formation are sufficiently simple and reliable to enable the practical use of such a system under real restoration workshop conditions.

The following diagrams present versions of the system incorporating various modifications, including filtering elements manufactured from carbon-carbon composite materials.

Figure 7.

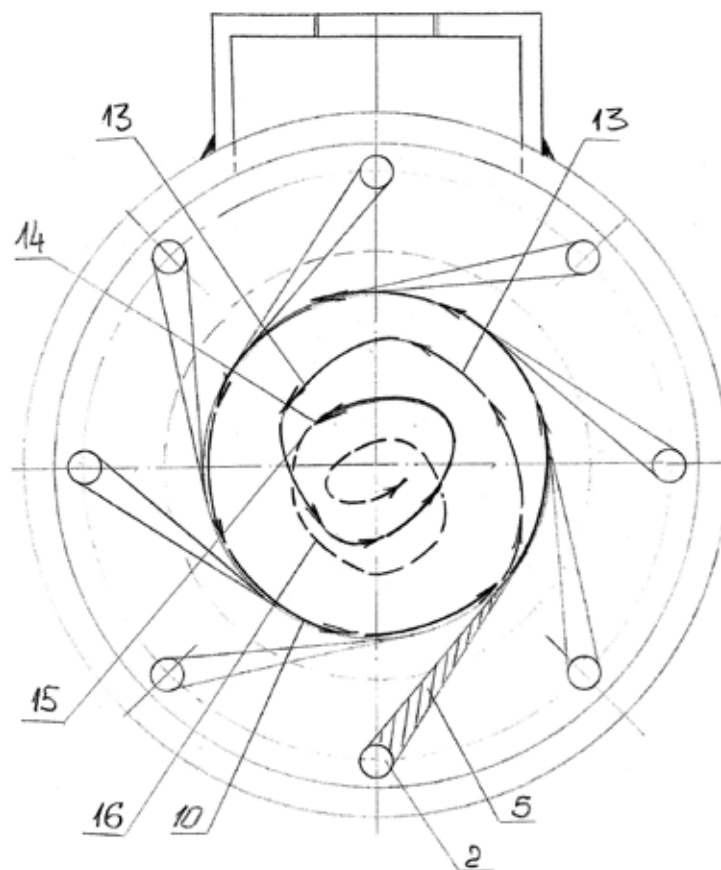
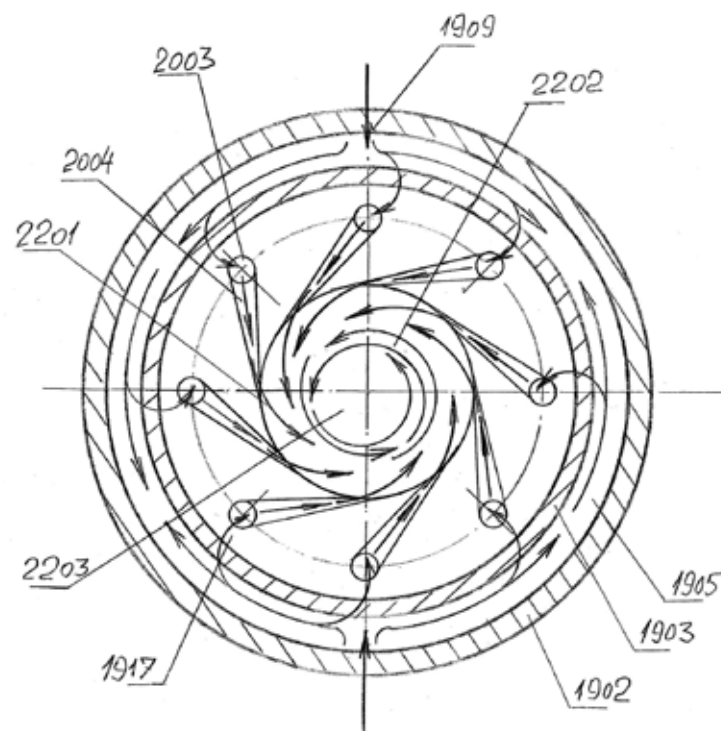


Figure 8.



After describing the vortex mixing system itself, the author proposes returning to the

question of selecting the oil component used as the paint medium.

In this regard, a new innovative technology for processing chicken eggs is proposed.

According to this technology, eggs – including non-standard or lower-grade eggs – are processed using a specialized method to produce an ultra-pure egg powder.

Subsequently, special solvents are used to extract alpha-lecithin from the powder. Alpha-lecithin serves as an equivalent to the oil medium used in paint production while significantly surpassing conventional oil in terms of purity.

Figure 9.

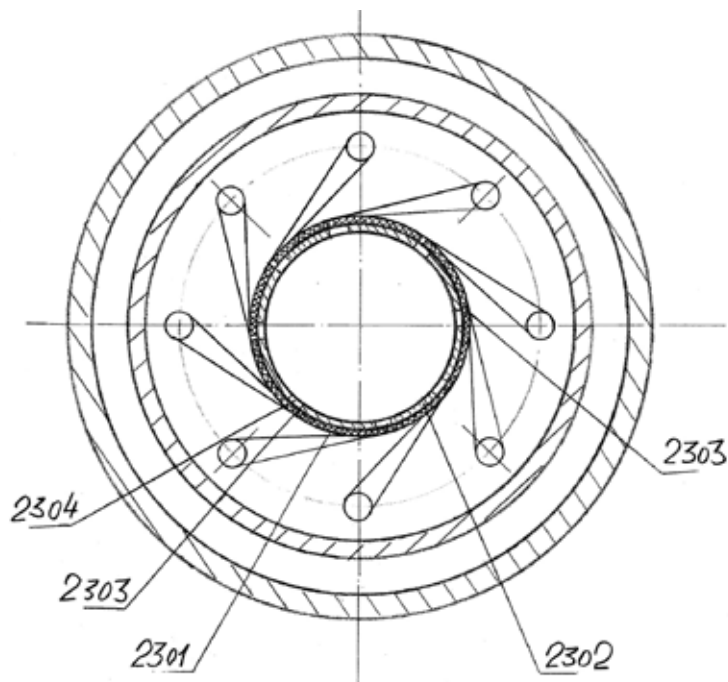


Figure 10.

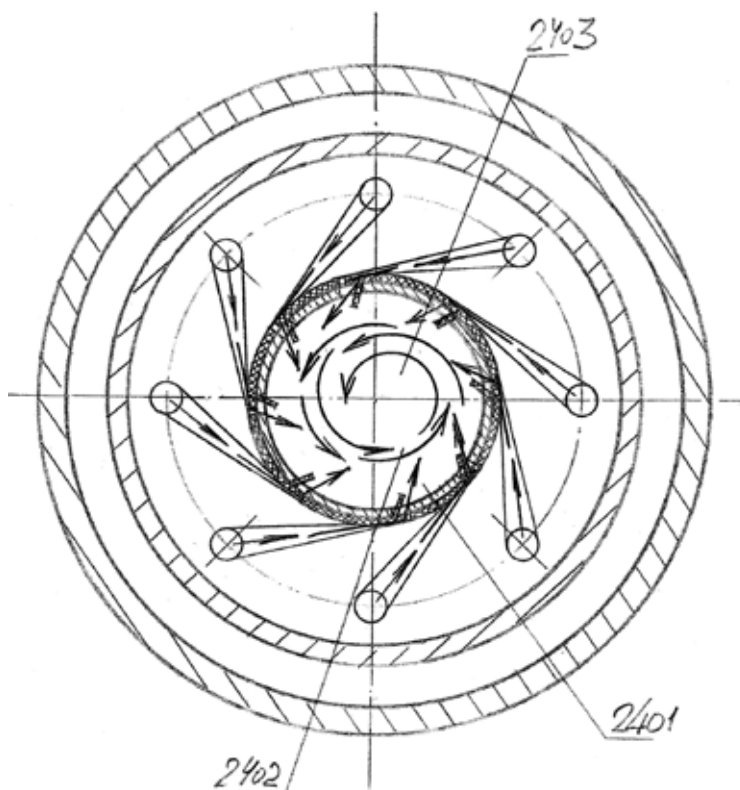
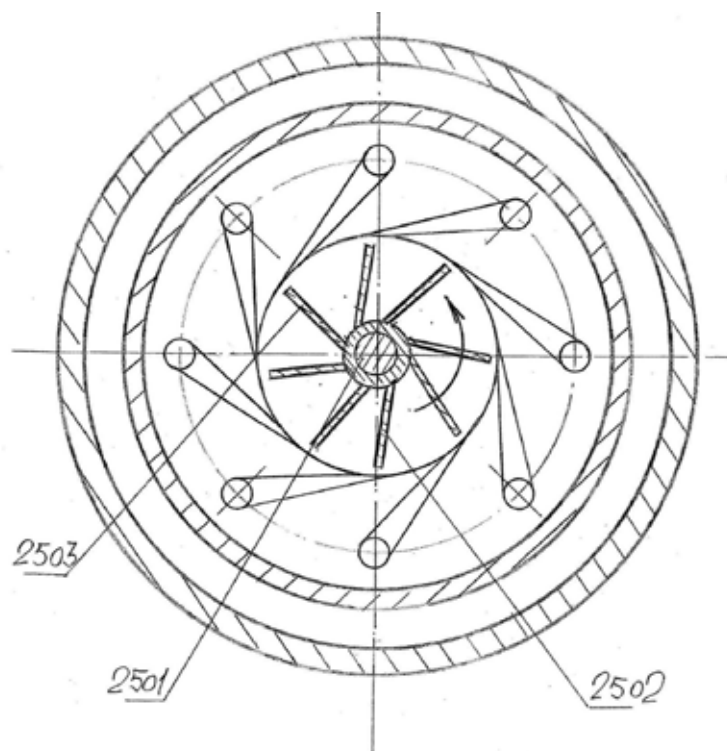


Figure 11.



During the same egg-processing procedure, ultra-pure lysozyme is also obtained as a natural preservative.

Thus, the proposed restoration paint is based on an entirely pure set of materials ultimately derived from the same chicken eggs traditionally used in paint production, but

processed to achieve a substantially higher level of purity.

According to the author, such a paint could significantly improve the cleanliness and quality of art restoration processes while extending the service life of restored paintings and enhancing their long-term preservation.

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submitted 26.05.2026;
accepted for publication 02.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-186-193



NEW DIRECTIONS IN MANUFACTURING TECHNOLOGIES FOR STRUCTURAL COMPONENTS

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Cite: Lysenko D. (2026). *New Directions in Manufacturing Technologies for Structural Components*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-186-193>

Abstract

This article examines the influence of manufacturing technologies for structural components on the successful development, commercialization, and industrial implementation of innovative products. Particular attention is devoted to the relationship between engineering design solutions and manufacturing methods, demonstrating that technological feasibility represents one of the fundamental conditions for the practical realization of innovative concepts.

The publication analyzes the necessity of integrating manufacturing technologies into the engineering design process from the earliest stages of product development. As an illustrative example, the study considers fuel injectors for internal combustion engines, where the achievement of critical performance characteristics – including micron-scale outlet orifices and reliable sealing under ultra-high fuel pressures – requires the application of advanced manufacturing technologies such as laser machining. The article emphasizes that the novelty of an invention should be considered not only from the perspective of product design but also in relation to the manufacturing technologies required for its production.

Special emphasis is placed on the influence of evolving consumer requirements, regional market conditions, and industry-specific standards on the commercial success of innovative products. The study examines the concept of emerging consumer standards as an important factor affecting engineering decisions, product functionality, operational characteristics, and commercialization strategies.

The publication concludes that the successful commercialization of innovative engineering products requires the comprehensive integration of advanced manufacturing technologies, engineering design, and market-oriented product development. Even when technological risks have been minimized through successful testing and validation, failure to satisfy contemporary consumer standards may significantly reduce the commercial viability of an otherwise technically successful innovation.

Keywords: *Digital technologies; Elements of artificial intelligence; Elements of artificial neural networks; Innovative products; Innovation analysis; Creative activity; Technical and technological stereotypes; Specific local domain; Overcoming technical, technological, and design stereotypes; The most effective and non-obvious technical solutions; Combined*

highly effective and non-obvious technical solutions; Foresight techniques; The potential for developing technical solutions with auxiliary innovative functionalities

Introduction

In integrated engineering solutions, the methods and technologies used for manufacturing product components and structural elements constitute one of the most important factors determining the practical feasibility of implementing an innovative product.

As an illustrative example, let us consider a fuel injector for an internal combustion engine. Fuel injectors represent one of the highest-volume engineering products manufactured worldwide, with annual global production exceeding one billion units.

The commercial and functional value of such a product is determined by several key engineering parameters, primarily the diameter of the outlet orifices and the ability to maintain complete sealing under extremely high fuel pressures, which may reach up to 2,000 bar.

The use of conventional drilling technologies imposes practical limitations on the mini-

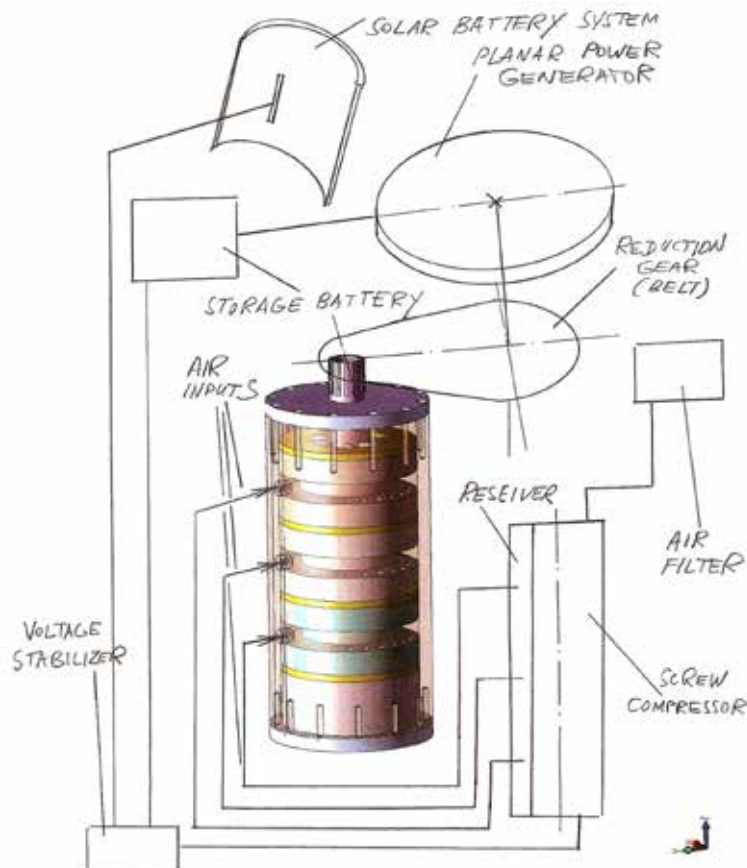
mum achievable diameter of these outlet openings. Since high-pressure fuel injection systems require orifices with diameters measured in micrometers, their manufacture requires advanced processing technologies, such as laser drilling.

Consequently, the inventor of a new fuel injector should incorporate into the inventive concept not only the structural novelty of the product itself but also the manufacturing-related innovations required to satisfy the specific technological requirements of laser machining equipment.

Emerging Consumer Standards

Continuously evolving market conditions and changing customer expectations, together with regional consumption patterns and national and cultural traditions, give rise to local consumer requirements that gradually develop into informal yet widely recognized consumer standards.

Figure 5. The figure presents the schematic diagram of the shoulder-mounted atmospheric water generator, illustrating the system configuration, electrical connections, and operating principle of the device for condensing potable water from ambient air



The designations of the individual components are provided in the figure.

If the objective of an inventor is to achieve commercial success for an innovative product, one of the fundamental elements of the commercialization strategy must be a thorough understanding of the prevailing consumer standards, including the required technical, operational, and functional characteristics expected of the product by its target market.

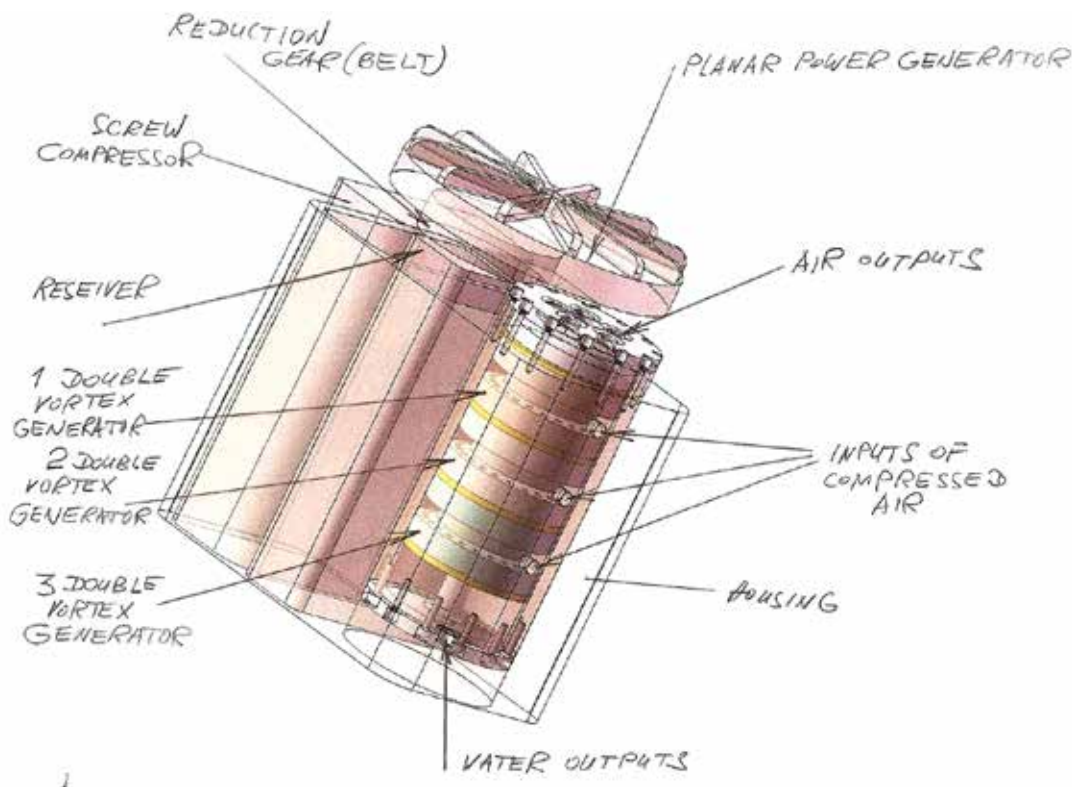
Even when technological risks have been successfully eliminated through comprehensive testing and validation of a new product, the risk of commercial failure may still remain. Such a risk exists whenever inventors and their commercialization partners fail to recognize or adequately understand the consumer standards governing the market for the proposed product.

As shown in the schematic, the device is powered by a miniature photovoltaic solar panel equipped with a voltage stabilizer connected to an energy storage battery.

The energy storage battery is, in turn, connected to a planar electric generator that supplies electrical power to all functional subsystems of the device, primarily to the dual vortex generators responsible for producing the vortex tubes in which the accelerated condensation process takes place. Air compression is performed by means of an innovative screw compressor.

Accordingly, the entire supersystem of the shoulder-mounted atmospheric water generator represents an integrated sequential assembly comprising several innovative subsystems. Both collectively and individually, these subsystems satisfy the criteria of non-obviousness required for innovative engineering solutions.

Figure 6. *The figure presents a three-dimensional conceptual model illustrating the configuration, interconnection, and operating principle of the shoulder-mounted atmospheric water generator designed for the condensation of potable water from ambient air. The principal assemblies and functional components of the system are identified and labeled in the figure*



The aerodynamic mechanism responsible for generating the primary vortex tube, which accumulates multiple localized vortex

tubes, consists of three dual localized vortex generators operating as an integrated aerodynamic system.

Figure 7. The figure presents a three-dimensional model of the vortex generator, which serves as the principal operating mechanism of the compact shoulder-mounted atmospheric water generator designed for the condensation of potable water from ambient air

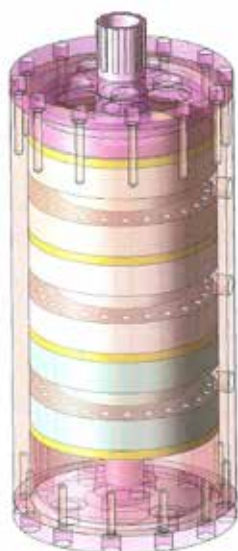
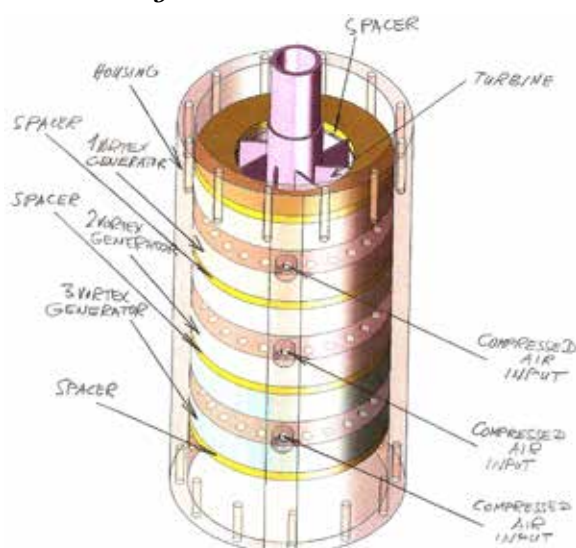


Figure 8. The figure presents a three-dimensional model of the central accumulating vortex generator, with the principal structural assemblies and functional components identified and designated in the illustration



It is appropriate at this stage to relate the structural characteristics and engineering features of the generator to the contemporary development of innovative technologies as integral components of intelligent technological systems.

The rapid evolution of software products, together with the increasing complexity of modern engineering systems – particularly electronic and microelectronic devices – has fundamentally transformed the principles governing their protection as non-obvious, multifunctional, and technologically integrated intellectual property.

Furthermore, the recent emergence of technical classifications such as **smart technologies**, **smart devices**, and **smart materials** has created the need for additional technical arguments capable of substantiating the inventive character of such engineering solutions.

For inventions of this type, structural features, circuit configurations, and combinations of engineering solutions alone are no longer sufficient to characterize the invention in its entirety. In many cases, these structural solutions can only be transformed into a functional system or prototype under specific manufacturing conditions and through specialized production and quality-control technologies. Consequently, the manufacturing process itself, combined with the demonstrated non-obviousness of the engineering design, frequently becomes one of the principal characteristics defining the inventive concept.

The continuing development of processor-based control systems likewise determines the practical viability of engineering solutions. As a result, control algorithms, software, data processing methods, and feedback mechanisms linking the structural or functional elements of a system have become an integral component of the technical solution underlying a modern invention.

This consideration should be supplemented by the results of systematic, step-by-step analysis of the innovative system together with the application of non-obvious methods involving artificial intelligence and artificial neural networks.

Accordingly, a modern invention frequently represents the integration of several distinct technologies within a single engineering concept. Such integration, together with the functional relationships established between the individual technological components, should be reflected in the patent claims in a manner that clearly demonstrates the unity of the inventive concept

and prevents the patent examiner from separating the invention into a number of independent technical solutions belonging to a single technological field.

The possibilities of integrative patent protection in the field of information technologies extend across virtually every sector of modern society.

Whereas technological sectors could previously be defined with relatively clear boundaries, the widespread penetration of advanced digital technologies and information technologies into all areas of engineering has fundamentally transformed both classification systems and intellectual property protection mechanisms, creating a new system of technical, commercial, and legal interrelationships that requires detailed substantiation of inventive step and non-obviousness.

Today, even relatively simple engineering systems and manufacturing processes increasingly incorporate technologies that did not previously exist. The emergence of new technological platforms, including quantum computing and related computational architectures, has resulted in engineering systems characterized by both horizontal and vertical technological integration. These systems combine technical methods, processes, and engineering principles that were previously unrelated and therefore constitute non-obvious technological combinations. Furthermore, the integration of conventional engineering solutions with the capabilities provided by modern information technologies has fundamentally transformed the concept of an invention itself, requiring that it be considered as a complex system of interrelated engineering solutions.

This technological evolution, occurring at the intersection of classical engineering disciplines and advanced digital technologies, has substantially changed the methodology for defining and protecting those structural elements and their combinations that may now be recognized as integrated engineering solutions satisfying the fundamental requirements of patentability and based upon composite engineering and manufacturing principles.

New Environmental Standards

Environmental regulations continue to become increasingly stringent worldwide. Consequently, during the development of

any innovative product whose operation may affect parameters regulated by environmental legislation, it is essential to ensure full compliance with all applicable environmental standards and regulatory requirements throughout the product's operational life.

Environmental standards are continuously revised and progressively strengthened. As a result, regulatory requirements that are currently acceptable are likely to become significantly more demanding within the next several years.

This consideration is particularly important in the development of energy systems, atmospheric water condensation technologies, internal combustion engines, and other engineering systems whose operational characteristics are directly influenced by environmental performance requirements.

Figure 9. The figure presents a three-dimensional model illustrating the airflow and water flow paths within the central accumulating vortex generator, which serves as the principal operating mechanism of the compact shoulder-mounted atmospheric water generator designed for the condensation of potable water from ambient air

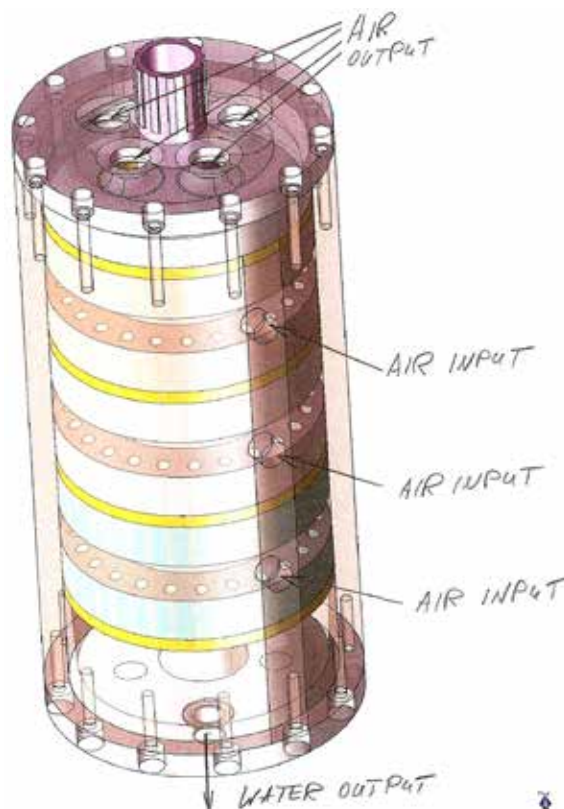
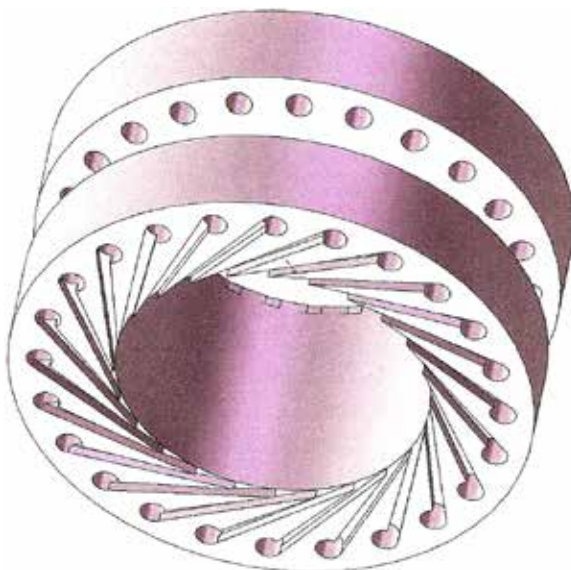


Figure 10. *The figure presents a three-dimensional model of the external configuration of the device designed for the condensation of potable water from atmospheric air*



Figure 11. *The figure presents a three-dimensional model of a local vortex-generator subsystem configured as a dual vortex generator. Air is introduced through the central annular channel, which is connected by axial passages to the individual vortex-generating elements*



The aerodynamic mechanism responsible for generating the primary vortex tube, which

accumulates the localized vortex tubes, consists of three dual localized vortex generators, each operating autonomously while contributing to the formation and stabilization of the central accumulating vortex flow.

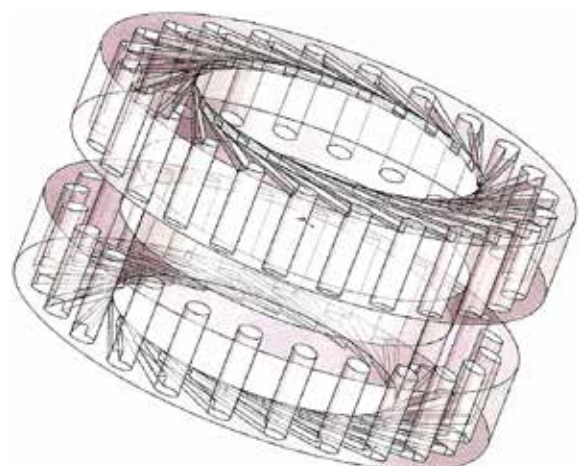
Availability of Fundamentally New and Non-Obvious Materials

As illustrative examples, two new engineering and technological directions may be considered: the development of highly efficient vortex tube generators and the design of composite vortex generators based on advanced mixing systems incorporating aerodynamic and hydrodynamic activation.

Both technological directions require the development and application of advanced structural materials whose physical and mechanical properties make it possible to achieve performance characteristics that cannot be attained using conventional engineering materials.

However, the application of such innovative materials is not unconditional. Their successful implementation requires an initial integrated engineering solution that combines both structural design and manufacturing technology, thereby creating the necessary conditions for the effective utilization of these materials within the proposed technical system.

Figure 12. *The figure presents a transparent three-dimensional model of a local vortex-generator subsystem configured as a dual vortex generator. Air is introduced through the central annular channel, which is connected by axial passages to the individual vortex-generating elements*



Considering the relatively complex structural configuration of the dual vortex generator, it is appropriate to revisit the environmental aspects that must be taken into account during the development of technically sophisticated innovative systems.

There are numerous examples in engineering practice where an innovative internal combustion engine incorporating a novel cylinder arrangement and an exceptionally efficient fuel-saving system nevertheless failed to satisfy future environmental requirements because the concentrations of nitrogen oxides (NO_x) and particulate emissions exceeded the limits established by an environmental standard scheduled to enter into force only two years later.

This circumstance alone was sufficient to require a complete redesign of the engine. As a result, the original engineering solution evolved into an integrated composite technological system through the incorporation of an innovative fuel preparation and activation subsystem that was functionally integrated with the original design. The implementation of this integrated technological solution made it possible to achieve a substantial reduction in the concentration of harmful emissions in the engine exhaust while preserving the principal performance advantages of the original design.

Figure 13. The figure shows a three-dimensional model of the local subsystem of the vortex generator in cross-section

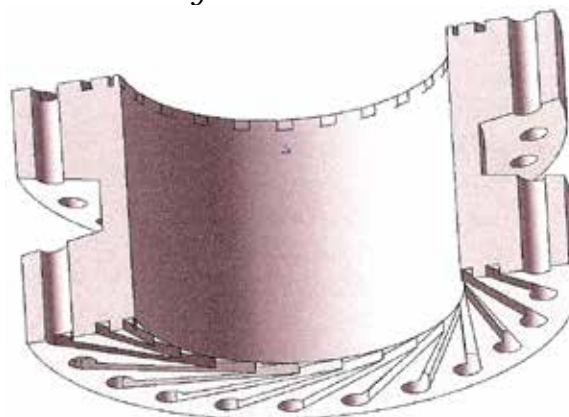
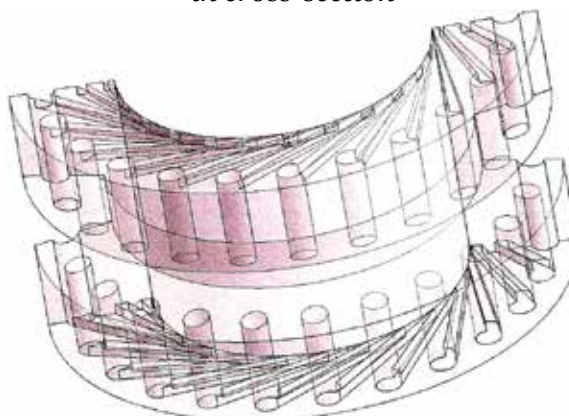


Figure 14. The figure shows a transparent three-dimensional model of the local subsystem of the vortex generator in cross-section



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submitted 15.06.2026;
accepted for publication 29.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-194-201



DEVELOPMENT OF DIGITAL TECHNOLOGIES INCORPORATING ELEMENTS OF ARTIFICIAL INTELLIGENCE AND ARTIFICIAL NEURAL NETWORKS.

(Modern multidisciplinary digital technologies incorporate elements of artificial intelligence and artificial neural networks, methods for achieving the ideal final result, as well as the nuances and aspects of marketing innovative products developed on the basis of and through the advancement of these technologies, in conjunction with innovative design)

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Cite: Lysenko D. (2026). Development of digital technologies incorporating elements of artificial intelligence and artificial neural networks. (Modern multidisciplinary digital technologies incorporate elements of artificial intelligence and artificial neural networks, methods for achieving the ideal final result, as well as the nuances and aspects of marketing innovative products developed on the basis of and through the advancement of these technologies, in conjunction with innovative design). Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-194-201>

Abstract

The article examines a number of fundamental factors that significantly influence the generation, development, evaluation, and commercial implementation of innovative technical solutions under the conditions of rapid digital transformation. Particular attention is devoted to the role of modern multidisciplinary digital technologies incorporating elements of artificial intelligence and artificial neural networks as instruments for enhancing inventive activity, innovation analysis, and the identification of effective technical solutions.

The study considers the distinction between practically applicable technical solutions capable of solving real technological and engineering problems and formal or speculative concepts that possess limited practical value despite their apparent novelty. The influence of technical stereotypes, technological paradigms, and associated psychological barriers on the formation and implementation of innovative ideas is analyzed. Special emphasis is placed on the mechanisms through which such barriers hinder the resolution of technical and technological contradictions and limit the emergence of non-obvious and highly effective engineering solutions.

The article further examines the impact of contemporary information technologies on the innovation process, including the substantial reduction of development cycles, increasing technological complexity of new products, rising costs of prototype creation and testing, and the growing importance of market-oriented innovation strategies. In this context, the necessity for

inventors and developers to possess multidisciplinary competencies extending beyond traditional engineering expertise is highlighted.

Particular attention is given to the integration of foresight methodologies, innovation-oriented analytical approaches, market demand assessment, and consumer behavior analysis with modern artificial intelligence technologies. The author emphasizes the importance of combining technical creativity, predictive capabilities, and commercial awareness in order to maximize the probability of successful implementation and commercialization of innovative products.

The article proposes several key directions that, under current technological and economic conditions, exert a decisive influence on the future development and market success of new technical ideas and innovative products. These directions are presented as practical guidelines for improving the effectiveness of innovation management and increasing the commercial viability of advanced technological solutions.

Keywords: *Digital technologies; Elements of artificial intelligence; Elements of artificial neural networks; Innovative products; Innovation analysis; Creative activity; Technical and technological stereotypes; Specific local domain; Overcoming technical, technological, and design stereotypes; The most effective and non-obvious technical solutions; Combined highly effective and non-obvious technical solutions; Foresight techniques; The potential for developing technical solutions with auxiliary innovative functionalities*

All inventors are aware that some technical solutions prove effective under real operating conditions, function successfully, and solve numerous practical problems. Such solutions often stimulate innovation analysis at the formulation stage and initiate purposeful creative activity on the part of the inventor. At the same time, there are artificially conceived and seemingly obvious technical solutions that are developed in isolation from practical reality and ultimately solve nothing beyond satisfying ambitious aspirations to create some form of technical or technological concept, which is frequently of little or no practical value.

Furthermore, technical solutions arising within any specific local field inevitably affect existing technical stereotypes and the psychological barriers that have emerged and continue to emerge on their basis. These barriers hinder the resolution of technical and technological contradictions that have developed as a consequence of such psychological limitations.

Twenty years ago, the necessity of generating inventions of the second category, as well as the equally important need to account for the influence of psychological barriers, could be justified by their auxiliary role in the selective identification of the most effective and non-obvious technical solutions from the broad spectrum of technical and combined creative ideas generated during the innovation process.

The emergence of information technologies and the substantial reduction of the time

cycle required to transform an inventive concept into a commercially demanded and practically implementable product, together with the increasing technical and technological complexity of modern products, which proportionally raises the cost of prototype development and testing, require a fundamentally new approach to the creation of technical solutions possessing auxiliary innovative functions while remaining highly non-obvious.

Today, if an inventor wishes his or her innovative ideas to be utilized in practice, it is no longer sufficient to rely solely on foresight techniques, intuition, and a well-developed imagination. The inventor must become a multidisciplinary specialist capable of understanding – or at least sensing – the commercial and consumer demands of the market, irrespective of prevailing stereotypes and the psychological barriers associated with them, which are often rooted in the apparent obviousness of the implementation pathways for synthesized ideas.

Several fundamental directions currently exert a decisive influence on the future of new ideas. Consideration of these directions can ensure a genuine and substantial level of commercial success, whereas neglecting them may permanently prevent an idea from being implemented in any commercial form.

The author proposes to examine several of these fundamental directions, recognizing that the scope of the present article allows only a concise thesis-based discussion.

Figure 1. *An example of modern innovative design featuring a complete simulation of the structural materials used, including their properties, performance characteristics, methods of mechanical processing, and types of finishing treatment.*



For contemporary technological innovations, which are often generated through intensive brainstorming involving large teams of specialists interested in achieving an effective result that may be considered an equivalent of the ideal final outcome, significant organizational challenges exist within the innovation process. These challenges arise from objective factors, including psychological, technological, and design stereotypes, as well as the apparent obviousness of emerging concepts and proposed solutions.

Emerging and continuously developing technical, compositional, and technological solutions are frequently evaluated through the prism of conclusions derived from the practical application of the laws governing the development and construction of industrial technologies, machines, and mechanisms established during the previous century, at a time when modern materials, components, assemblies, advanced industrial electronics, and laser technologies were unknown.

Moreover, the integration of artificial intelligence and artificial neural network elements into the infrastructure of new technical systems significantly complicates the design process and the formation of the technical and technological characteristics of innovative products.

This situation is further complicated by the fact that, as noted in the first part of this publication, recognition of a technical solution as an invention is based on different criteria in the United States and in most other countries. In the United States, patentability is assessed according to four criteria, whereas in most other jurisdictions three criteria are generally applied.

The fourth criterion is precisely the subjective evaluation factor that gradually initiates and reinforces the psychological stereotype based on the division of new technical solutions into obvious and non-obvious categories.

The presence of a clearly expressed subjective factor introduces into the evaluation process comparisons with known design and technological elements and their combinations derived from previously developed solutions.

The familiarity of a particular solution and all aspects of its implementation cannot constitute an objective factor, since the determination of whether a technical solution is obvious or non-obvious fundamentally depends on the knowledge, experience, and professional competence of the experts conducting the evaluation.

In modern engineering and technological developments, novelty is no longer a reflection of a single technical discipline. Rather,

it represents the integration of multiple disciplines, including electronics, microelectronics, advanced materials science, fiber-optic technologies, and laser engineering. Consequently, the assessment of obviousness or

non-obviousness must be conducted from multiple disciplinary perspectives and can be performed effectively only through the joint participation of highly specialized experts together with specialists in systems integration.

Figure 1–1. *The figure illustrates alternative industrial configurations of the devices presented in Figure 1, incorporating three-dimensional analysis of the scale factor, together with a parallel assessment of the level of non-obviousness associated with the entire set of engineering, technological, and design solutions integrated into this innovative product*

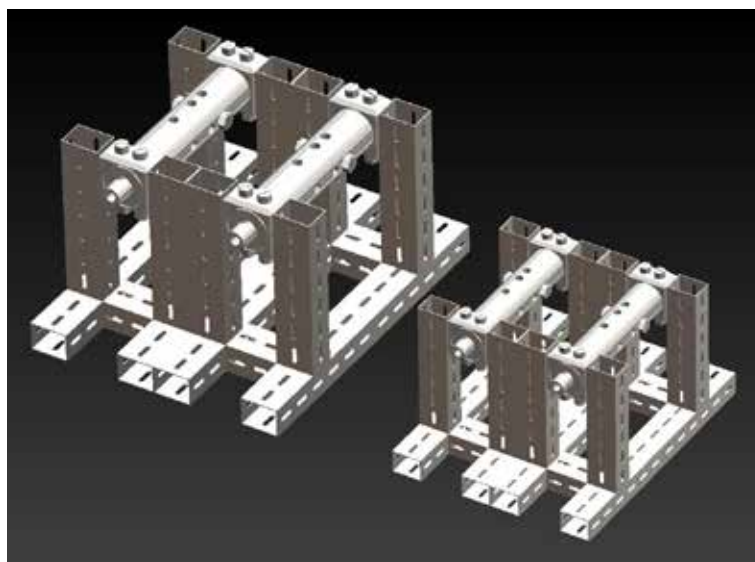


Figure 2. *An example of modern innovative design utilizing sectional views, accompanied by technical and innovation-oriented analysis aimed at substantiating and evaluating the degree of non-obviousness of all device components, as well as the corresponding non-obviousness of the functional characteristics of assembly associations and the subsequent commercial advantages derived from these characteristics*



Within every technical discipline, certain standard solutions gradually become established over time and eventually evolve into stereotypes that are familiar to virtually all practicing specialists in the respective field.

Such stereotypes become deeply embedded in everyday engineering practice, and any modification of a design or technology encounters a certain level of resistance, which, over time, develops into a well-defined technological and psychological barrier.

Under these circumstances, the effective generation of innovative ideas through brainstorming techniques, as well as the refinement of these ideas and their innovative combinations toward achieving a boundary-level ideal final result, may encounter – and in practice frequently do encounter – stereotypical psychological barriers. Even when a portion of the working group generates technically viable proposals that are non-obvious to an average specialist within a particular industry, such proposals may not be unequivocally accepted and, especially during the initial stages of evaluation, are often rejected.

If one turns to the Theory of Inventive Problem Solving (TRIZ) and its methodologies for achieving the Ideal Final Result (IFR), it becomes apparent that this theory is not entirely adequate under the conditions of contemporary integrative and highly complex technical solutions.

Moreover, even prior to the emergence of such solutions, the Theory of Inventive Problem Solving possessed a number of significant limitations that evidently contributed to the stagnation of its development following the death of its author and created substantial difficulties in its practical application.

What were the principal limitations of this approach?

Within the framework of TRIZ, and in accordance with the technological realities of its time, an attempt was made to formulate universal laws governing the development of technical systems that would serve as the foundation for a general problem-solving methodology.

These principles remained relevant until the emergence and widespread implementation of processor-based technologies and the subsequent adaptation of classical ideal-

result concepts to new technological paradigms. The effectiveness of these paradigms became determined not only by the quality of engineering and technological solutions and their combinations but also by the sophistication of the software systems integrated with them, which introduced fundamentally new commercial characteristics to innovative products and inventions.

However, many of the principles and laws formulated more than seventy years ago can no longer be regarded as universal laws under the conditions of extensive digital transformation and the widespread implementation of modern information technologies.

They should more appropriately be regarded as developmental patterns or tendencies in technological evolution, and even then as incomplete representations of the innovation process. Consequently, a comprehensive and coherent methodology for problem solving based exclusively on such laws never fully emerged.

The formulated laws were primarily employed as methodological explanations for illustrative examples of inventions rather than as a complete framework for innovation development. Factors of commercial feasibility were largely excluded from consideration, and insufficient attention was paid to the influence of market requirements on the application and continuous modification of the evolving principles governing technical systems.

As a result, limited consideration was given to the possibility of adapting, optimizing, and modifying technical objects in a manner that could transform an invention through evolutionary development into a non-obvious, commercially viable, and fully market-demanded innovative product at a fundamentally new level of commercial utilization.

Recent patent disputes among the world's largest technology companies clearly demonstrate that the traditional laws governing the development of technical systems are no longer capable of reflecting the full diversity of functions, characteristics, and challenges associated with modern multifunctional products whose structural features exhibit a high degree of non-obviousness. Taking into account the numerous new factors that characterize contemporary innovative products and continue to emerge as a result

of technological progress, there is a need to reformulate these laws by linking them with the principles governing the development of commercial structures, the commercializa-

tion of innovative ideas, the infrastructure of the modern innovation economy, and the practical globalization of innovation processes.

Figures 3 and 4. *Examples of combinatorial innovative design developed on the principles of overcoming technological stereotypes*



The dialectical approach based on contradiction analysis, which formed the foundation of the principal problem-solving methodology, was substantially modified through the introduction of new concepts, including technical and physical contradictions. These concepts significantly altered the essence of the dialectical contradiction originally formulated within classical dialectical logic, thereby creating difficulties in identifying contradictions when addressing real-world inventive problems. Furthermore, this approach failed to adequately assess the degree of non-obviousness of technical solutions, particularly those incorporating elements of artificial intelligence and artificial neural networks.

In this context, and considering the extensive integration of digital technologies and software applications into classical engineering solutions, special attention should be devoted to several fundamental questions. What should be considered a genuine inventive problem? How can the differing perspectives of inventors, manufacturers, and consumers be harmoniously integrated into the evaluation process? To what extent can the correct or incorrect formulation of an inventive problem influence the commercialization potential of the resulting invention? Is it possible to reliably protect complex integrated technical solutions against unauthorized replication and imitation?

The search for answers to these and many other questions has become an essential component of modern patenting and licensing strategies and must inevitably be combined with a rigorous assessment of the degree of non-obviousness associated with innovative technical solutions.

The further development and modification of the algorithm underlying inventive problem-solving methodologies did not proceed through the elimination of inaccuracies in contradiction-identification procedures. Instead, the process largely followed a path of increasing complexity. As a result, the final official version of the algorithm evolved into an extremely cumbersome structure with limited practical applicability.

At the same time, no clear mechanisms were established for transitioning from a formally identified contradiction to its practical resolution. This created substantial difficulties in addressing real engineering and technological challenges.

Although the theory formally declared a departure from methodologies based on extensive enumeration of possible alternatives, the majority of the so-called problem-solving instruments effectively represented precisely such methods.

This analytical framework was presented as a scientific approach grounded in the study of patterns governing the structural evolution of technical systems. However, the acceptance of hypothetical physical fields that do not exist in reality, together with the possibility of ambiguous interpretations of structural models and transformation rules, suggests that the methodology should more appropriately be classified as a technique for stimulating variant generation rather than as a rigorous scientific analytical framework.

The approach most closely aligned with the objective of formalizing inventive problem-solving procedures was the devel-

opment of contradiction matrices and associated principles for resolving technical contradictions. This methodology was based on statistical analyses of patent descriptions and invention disclosures available at that time. Nevertheless, despite its potential, it did not receive substantial further development and, due to a number of inherent limitations and the progressive obsolescence of its statistical foundations, gradually lost its practical relevance.

There remains a widespread misconception regarding the possibility of directly integrating such methodologies into industrial production environments. In essence, these approaches constitute individual problem-solving methods whose application depends largely upon personal choice and individual creative preferences. Consequently, a significant psychological component is inherently involved in their utilization. For this reason, it is impossible to transform such methodologies into a fully integrated component of a manufacturing process. At most, enterprises can organize training programs aimed at enhancing the creative capabilities of their personnel, a practice that continues to be employed by numerous organizations in the United States.

During the period of their most active development in the 1980s, many of these shortcomings were effectively compensated for by the enthusiasm of innovation advocates and practitioners. Nevertheless, the existing limitations, combined with the decline of the original development community capable of recognizing and addressing these deficiencies, ultimately led to stagnation in the further evolution of the methodology.

In the author's opinion, this represents the primary reason why, over recent decades, no fundamentally new developments of significant theoretical or practical importance have emerged within this field.

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submitted 02.06.2026;
accepted for publication 16.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-202-206



**POTENTIAL PARTNERS FOR THE ESTABLISHMENT AND
DEVELOPMENT OF TECHNOLOGY INCUBATORS IN UKRAINE.
(Strategic partnership structure for the establishment
and operation of technology incubators in Ukraine)**

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Cite: Malyeryk Kh. (2026). *Potential partners for the establishment and development of technology incubators in Ukraine. (Strategic partnership structure for the establishment and operation of technology incubators in Ukraine). Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-202-206>

Abstract

This article examines the strategic importance of international cooperation in the establishment and development of technology incubators in Ukraine, with particular emphasis on the role of foreign scientific, engineering, and investment partners in strengthening the national innovation ecosystem. The publication analyzes organizational approaches to building international partnerships capable of accelerating the commercialization of innovative technologies and supporting the sustainable development of high-technology enterprises.

Particular attention is devoted to the potential for scientific and technological cooperation between Ukraine and Israel, taking into account the favorable conditions for professional interaction, the common engineering and scientific traditions shared by many specialists, and the opportunities for expanding collaborative research, technology transfer, and joint innovation projects. The article identifies priority technological fields in which international cooperation may produce the greatest practical and economic benefits, including advanced composite materials, superhard materials, electron microscopy, carbon-based engineering materials, and modern agricultural technologies.

The publication further considers the contribution of international experts, research institutions, industrial enterprises, venture investors, and technology commercialization specialists to the successful operation of technology incubators. It emphasizes the importance of integrating global scientific expertise, engineering competencies, and investment resources into the national innovation infrastructure in order to accelerate the development, commercialization, and international competitiveness of advanced technological projects.

Special consideration is also given to the prospects for expanding international cooperation in specialized fields of innovation, including medical technologies, which are recognized as an important area for future research and separate analytical consideration within the broader framework of technology transfer and innovation management.

Keywords: *Technology incubator; Innovation ecosystem; Effective implementation; Innovative development model of industrial and agricultural production; Ecosystem infrastructure framework; Quantum computing; Augmented reality visualization; Testing laboratories; Laws of technical system evolution; Standardization; Technology transfer*

Introduction

The foremost and most important partner is, naturally, people themselves – professionals, innovators, and the initiators of innovative ideas and projects.

The second essential and equally important partner, serving in part as an organizer, is represented by government authorities, local self-government bodies, regional and district administrations, and, where appropriate, legislative authorities.

The third professional partner consists of intellectual property specialists, patent attorneys, registered patent agents, and legal professionals specializing in patent law.

The fourth partner comprises standardization authorities and laboratories, testing and measurement laboratories, state technical supervisory authorities, including industrial and mining safety inspection bodies, and other relevant regulatory organizations.

The fifth partner includes academic and industry-oriented research institutes, universities, higher education institutions, tech-

nical colleges, and other specialized educational and scientific organizations.

The sixth partner consists of established industrial enterprises that have successfully preserved their manufacturing capabilities and maintained their positions in the marketplace.

The seventh partner does not yet fully exist in practice; however, it is expected to become one of the most important participants in the innovation ecosystem. This partner includes venture capital funds and other investment institutions, whose development should be encouraged through appropriate legislative initiatives, as well as systems of financial and tax incentives designed to stimulate investment in innovation.

During the period in which this seventh partner is still being established and developed, there are favorable opportunities to involve comparable international venture capital funds and independent private investors from abroad as participants in this partnership framework.

Figure 1.



Who Should Be Invited to Cooperate in the Organization and Initial Development of Technology Incubators in Ukraine

As announced in February 2011, the visa-free travel agreement between Israel and Ukraine entered into force.

This means that there is no longer a need to spend time and financial resources on obtaining visas, and, when necessary, travel between Ukraine and Israel can take

place as freely as travel within Ukraine itself.

Naturally, this significantly simplifies contacts, including professional cooperation.

Considering that every eighth resident of Israel is Russian-speaking and shares the same technical culture and professional mentality as specialists from Ukraine, it can be concluded that professional cooperation between the two countries has the potential to be exceptionally productive, efficient, and

beneficial, without requiring additional expenditures for interpreters or similar services.

If one analyzes the experience accumulated by Israeli specialists in numerous sectors of industry and agriculture that are also of potential interest to Ukraine, several areas can be identified as being of particular importance and interest, where cooperation could produce the fastest and most significant results.

These include expertise in the development of superhard materials and composites based on such materials, experience in the development and effective application of electron microscopes, expertise in the creation of unique carbon composites and advanced materials, and, finally, Israel's extensive and internationally recognized experience in all areas of agricultural production and animal husbandry.

Medical technologies constitute a separate and particularly important area of the innovation process. It would therefore be appropriate to return to this subject and consid-

er the experience of their development and implementation in a separate publication.

Figure 2.

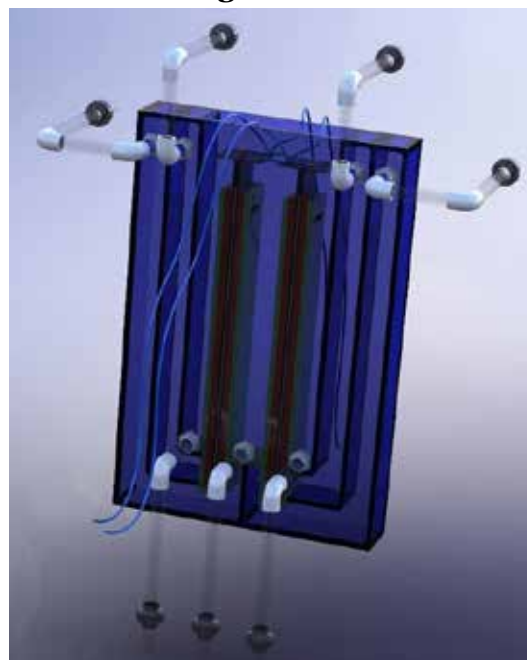
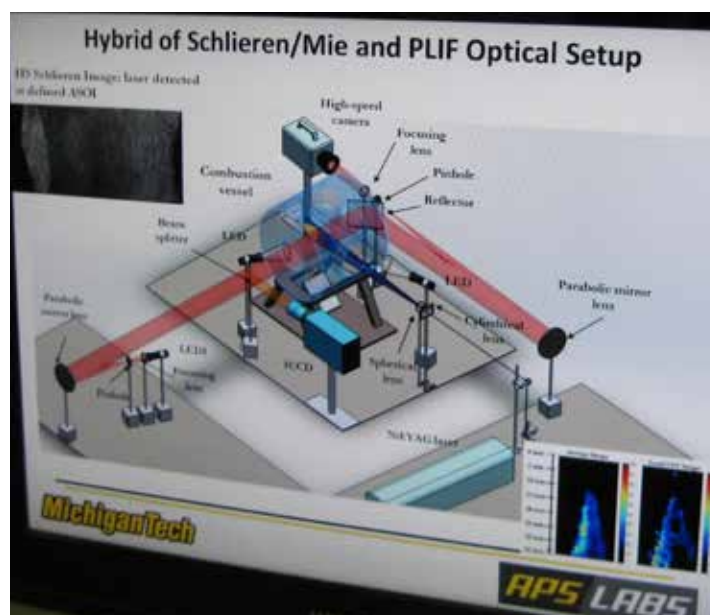


Figure 3.



Inventions Opening an Innovative Scientific and Technical Service Direction for the Visualization of Augmented Reality and Its Wide-Scale Application

Augmented reality technologies for consumer and personal optical devices are still in the early stages of development. However, considering the possibilities for both horizontal and vertical integration of these technologies and their derivatives into personal

and public infrastructure, they are expected to have a significant future.

Headsets utilizing the above-mentioned augmented reality technologies, as well as their initial applications and combinations, are currently relatively expensive, and wearing them throughout the day remains inconvenient. Nevertheless, the predicted and anticipated growth of consumer interest in these groups of technologies and their com-

binations makes it necessary to conduct an active analytical review of this field.

Since the service and operational aspects of products based on these and similar groups of technologies, together with the various innovative technical solutions associated with them, have not yet been adequately addressed, the author of this article, drawing upon personal experience in organizing service support for various consumer and personal optical applications, considers it appropriate to propose several ideas and recommendations in this area.

Augmented reality (AR) is understood as the technology of superimposing virtual objects onto a person's view of the real world.

The most common consumer applications of this technology are AR browsers and AR glasses.

In AR browsers, virtual objects are superimposed onto images captured by a smartphone or tablet camera, while in AR glasses they are projected onto a lens or displayed on a miniature monitor.

Specialists and experts continue to analyze the prospects for the commercial success of products based on these technologies when introduced to the market. During these discussions, a number of interesting details and circumstances have emerged, the proper understanding of which may provide practical assistance in achieving comprehensive positive results.

A considerable amount of time has passed since the release of the first relatively successful augmented reality glasses project; however, there is still no clear understanding of what the optimal design version of such glasses should be.

From the very first moments of use, these glasses created a growing sense of uncertainty regarding their role and their potential influence on increasing commercial activity within the market for similar products. Despite all expectations, after users had sufficient time to learn how to use the new device effectively and their initial enthusiasm had diminished, interest gradually declined, while a clear understanding of the reasons for this situation failed to emerge.

The fact remains that throughout this period developers have been unable to transform augmented reality glasses into a device

as familiar and indispensable as a smartphone, a gaming console, or a smartwatch.

In the author's opinion, one of the reasons for this situation is the current state of service technologies, which are not yet prepared to support such complex devices under conditions of mass production and widespread consumer use.

Today, one of the principal indicators of both public interest in and the relevance of this technology is the current state of patent protection relating to these emerging technologies, which, upon closer examination, raises numerous questions.

It is surprising that, despite the fact that augmented reality visualization projects and technologies, both independently and in combination with related technologies, have the potential – through integration with existing digital technologies – to create entirely new technological fields and promise rapid growth in market demand, the pace of patent protection remains relatively slow and limited.

During a patent search conducted by the author using keywords in the database of the United States Patent and Trademark Office (USPTO), only 133 patent applications were identified, while no issued patents were found on this subject:

- **Glasses of additional reality** – only 113 patent applications were registered.
- **Visualization of additional reality** – only 20 patent applications were registered.

An initial analysis of the published patent applications demonstrated that all of these applications are exploratory in nature and do not focus on the design and systems of augmented reality glasses as mature commercial products. Furthermore, all of the examples relate to products that remain at the final stages of development, indicating a genuine lack of practical experience in servicing and operating such devices.

Since the author of this series of publications is engaged in the practical implementation of these products within a specific market, it is evident that, at the present stage, numerous technical solutions and supporting tools required for their successful commercialization are still lacking. Among the first

priorities are technical solutions and products intended to support the everyday use of augmented reality glasses, including technologies for cleaning the lenses from unavoidable contamination arising during normal use, whether of organic or inorganic origin.

Since the lenses of augmented reality glasses become contaminated in much the

same way as those of conventional eyewear, from a practical perspective one of the first priorities should be the development of an integrated technology for producing cleaning and disinfecting solutions using water that does not contain high concentrations of dissolved salts, including hardness salts.

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submitted 15.06.2026;
accepted for publication 29.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-207-213



STAGES AND PHASES OF PROJECT ADVANCEMENT FROM CONCEPT TO COMMERCIAL IMPLEMENTATION. (Technology incubators as mechanisms for innovation commercialization and startup development)

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Cite: Malyeryk Kh. (2026). *Stages and Phases of Project Advancement from Concept to Commercial Implementation. (Technology incubators as mechanisms for innovation commercialization and startup development)*. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-207-213>

Abstract

This article examines the organizational, technological, legal, and commercial aspects of advancing innovative projects from the stage of conceptual development to successful market implementation. Particular attention is given to the sequence of stages and phases involved in project development, the formation of effective commercialization strategies, and the role of technology incubators as institutional mechanisms supporting innovation-driven enterprises.

The study analyzes the importance of patent and licensing strategies as fundamental components of the innovation process and highlights the significance of cooperation with patent attorneys in securing intellectual property rights and strengthening the competitive position of innovative products. The publication also considers the role of technology commercialization specialists in facilitating project financing, market positioning, and the successful transition of technological developments into commercial products.

Special emphasis is placed on the requirements imposed on projects developed within technology incubators. The article outlines the recommended structure of intellectual property assets, technical documentation, engineering models, research reports, prototype testing programs, manufacturing documentation, and supporting materials required for the effective evaluation and development of innovation projects.

The publication further examines organizational models for establishing and operating technology incubators, including mechanisms of interaction between inventors, investors, incubator management teams, engineering specialists, and commercialization experts. Particular attention is devoted to investment structures, project financing mechanisms, equity distribution models, and approaches to risk management during the implementation of innovative ventures.

The study demonstrates that technology incubators serve as effective instruments for accelerating innovation, facilitating the commercialization of scientific and engineering achievements, attracting investment capital, and creating favorable conditions for the development of sustainable high-technology enterprises. By integrating technological expertise, intellectual property

management, investment support, and commercialization strategies, technology incubators contribute significantly to economic modernization and the formation of innovation-driven industries.

Keywords: *Technology incubator; Innovation ecosystem; Effective implementation; Innovative development model of industrial and agricultural production; Ecosystem infrastructure framework; Quantum computing; Augmented reality visualization; Testing laboratories; Laws of technical system evolution; Standardization; Technology transfer*

Introduction

This is a highly specialized issue that varies significantly depending on the specific characteristics of the project and its position within the market.

It can be stated that, in innovative projects, this process does not differ substantially from conventionally accepted approaches and is optimized according to numerous influencing factors. In practical implementation, the determination of the nature and sequence of stages and phases is often carried out in accordance with specialized matrices and tables developed by the project initiators. More detailed information on these methodologies is available in dedicated publications presented on innovation-oriented websites.

Cooperation with the Patent Attorney Community

Since patent strategy and patent protection of innovative initiatives constitute an exceptionally important component of the innovation process, cooperation with patent attorneys and the selection of an appropriate attorney are among the key prerequisites for successful project advancement, particularly during the initial stages.

In order to make this process more predictable and to achieve a more reliably forecasted final result, patent and licensing strategies are generally developed before engaging patent attorneys, taking into account the numerous specific factors inherent to the innovation.

To obtain more favorable conditions for such work and to achieve stronger technological and legal outcomes, the principle of maintaining a high level of competition among patent attorneys is fully utilized, thereby ensuring the desired result.

Cooperation with Specialists in Project and Technology Commercialization

In practice, the innovation ecosystem is continuously populated by commercializa-

tion specialists representing various schools of thought and levels of expertise. The proper competitive selection of such specialists can significantly influence the availability of more favorable project financing conditions and provide a shorter and more successful path toward commercial implementation.

The selection of such a specialist is an important process, and the success of this selection is largely determined by the prior choice of a company capable of assisting in the evaluation of the innovation project and its correct technological classification.

Requirements for Projects Developed within Technology Incubators

When presenting a project to an intermediary company, the project materials should contain, or it is strongly recommended that they contain, the following documents and materials:

Composition and Structure of Intellectual Property Assets Owned by the Company or the Project Applicant Group

As a rule, all technological areas being developed by the project applicant company at various stages constitute complex intellectual property assets.

Each technological area should be represented by a structured system of component elements, including the following principal documents:

- Forecast of the technological development of the respective field for both short-term and long-term perspectives;
- Patent and licensing strategy covering all products within the technological field, including all project stages and all stages of production and marketing;
- Fundamental and core invention patents forming the basis of the technological field;

- Application patents generated through the development of the technological field;
 - Inventions created by employees and partners of the applicant company prior to the establishment of the applicant company, for which inventor's certificates, patent rights, or other legal documentation are held by the respective employee or partner;
 - Research and development reports generated by employees and partners of the applicant company relating to the technological field and performed outside the framework of the applicant company;
 - SolidWorks models for all product modifications within the technological field, including all assemblies, sub-assemblies, components, parts, and models intended for digital and virtual simulation of product operation;
 - Fundamental manufacturing principles for parts and assemblies associated with products of the technological field;
 - Complete sets of engineering design and manufacturing documentation required for the production of products within the technological field;
 - Optimized CNC machine programs intended for the production of prototypes and pilot samples of products within the technological field;
 - Testing programs and methodologies covering all required categories of prototype testing and product testing throughout all stages of production;
 - Operational models of innovative products within the technological field and field-test results relating to technological products in agricultural applications;
 - Operating and supporting documentation for products of the technological field, including technical instructions relating to installation, preservation, storage, maintenance, repair, and transportation;
 - Functional prototypes of products within the technological field;
 - Technical descriptions of the principles and design of specialized manufacturing equipment used for the production of key components and assembly of products within the technological field, together with materials intended for the preparation of patent applications relating to such specialized manufacturing equipment.
- Naturally, this represents only an illustrative structure of the required documentation. For each individual project, depending on its specific characteristics, implementation conditions, market-entry strategy, and the requirements of potential investors, this list may be substantially modified.
- Particular attention should be given to projects in the fields of biotechnology and genetic engineering. Such projects will most likely require specialized technological, scientific, commercial, and expert evaluation procedures tailored specifically to these areas.

Figure 1.



Figure 2.

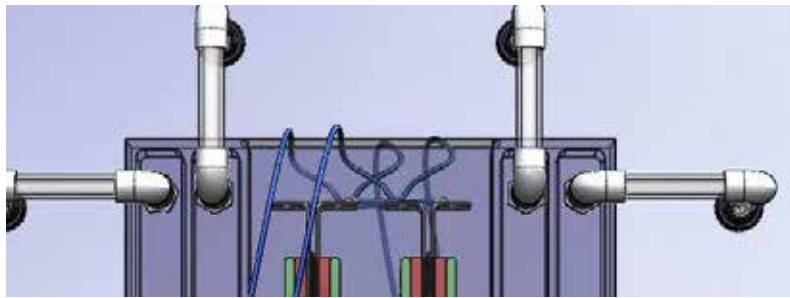


Figure 3.



Proposal for Possible Models of Technology Incubator Development in Ukraine

Ukraine possesses all the necessary conditions and prerequisites for the establishment and successful operation of technology incubators.

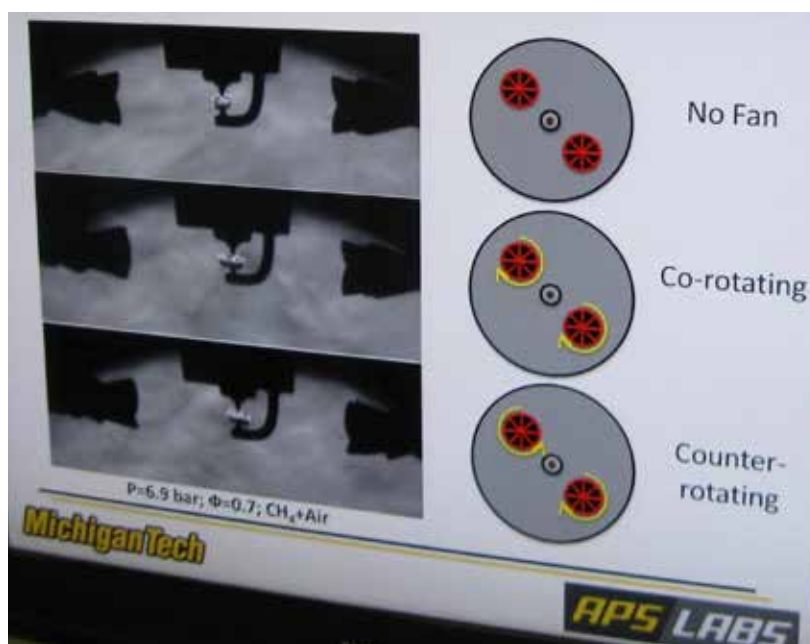
Thousands of highly qualified specialists are actively employed across the country. Over many years of stable operation within the defense-industrial sector, a vast body of manufacturing and engineering expertise has been accumulated. Engineering personnel have been educated and trained over several generations, and the level of professional expertise achieved by these specialists fully meets the highest requirements for the initiation and development of innovative technological solutions.

Ukraine has also accumulated unique experience in agricultural production. This experience, combined with exceptional natural conditions that have virtually no analogues

anywhere in the world – one prominent example being the famous Ukrainian black soil (chernozem)—creates highly favorable conditions for the establishment of agricultural enterprises capable of achieving exceptionally high levels of efficiency, productivity, and profitability.

These factors provide a solid foundation for the development of technology incubators focused on agricultural innovation, advanced manufacturing, environmental technologies, industrial automation, information technologies, and other high-technology sectors. By combining scientific knowledge, engineering expertise, industrial experience, and natural resources, technology incubators in Ukraine can become effective platforms for the creation, development, and commercialization of innovative products and technologies capable of competing successfully in international markets.

Figure 4. *Turbulence Effects*



Proposal for the Organization of Technology Incubators in Ukraine

Naturally, it is neither possible nor advisable to immediately cover the entire territory of Ukraine with a network of technology incubators, since, despite their technological and commercial transformative potential, the creation of highly effective technology incubators remains an evolutionary process.

The organization of the first stages in the development of technology incubators in Ukraine appears feasible and advisable in the following sequence:

- First and foremost, based on the opinions of Ukrainian experts, it is necessary to identify the technological sector in which Ukraine possesses the highest aggregate scientific, commercial, and historically established competitive potential;
- It is not advisable to make premature forecasts or assumptions. In our view, the most appropriate approach would be to announce competitions for the best technological projects across all sectors of production, particularly in agriculture, throughout all regions of Ukraine.

To evaluate the technical and commercial merits of the proposed projects, it would be advisable to establish competition criteria

and an expert review panel. During the first stage of evaluation, it would be beneficial to invite specialists in the commercialization of innovative technologies from the United States (individuals already expressing interest in participating have been identified). During the second evaluation stage, when the most promising projects have been selected, representatives of various investment funds should be invited to participate in the assessment process, particularly those possessing experience in investment activities within the Russian market. Some of these organizations have already been preliminarily introduced to the concept of establishing technology incubators in Ukraine, have expressed initial interest, and understand the requirements necessary for successful implementation.

In this proposal, the operational scope of a technology greenhouse (or incubator) established in one of Ukraine's regions is divided into domestic activities within Ukraine and international cooperation activities.

Within the framework of operations in the Ukrainian technology market, the following sequence of organizational and technical stages is proposed for project initiators and inventors, assuming that a technology incubator has already been established:

1. Initial Project Preparation

The project initiator or inventor prepares the required informational and technical

documentation and secures an initial private or other investor willing to invest no less than USD50,000.

If the inventors or project initiators encounter difficulties in identifying such an investor, it may be advisable to engage a consulting company for assistance.

2. Establishment of the Project within the Technology Incubator

After securing the first private investor, the innovators, possibly together with the investor or an authorized representative of the investor, present the project to the technology incubator.

Under predefined standard conditions established by the technology incubator, the project is formally organized, and a new innovative company is created on its basis.

It is appropriate at this point to briefly describe these standard conditions.

Drawing upon existing experience, investments in the new company should include private investment of approximately USD50,000. This amount represents a minimum threshold; private investments may be significantly larger if the investor has sufficient confidence in the project.

The remaining funds required for project implementation are provided by the technology incubator. According to practical experience, this amount is approximately USD400,000.

Neither the private investor nor the incubator contributes the full amount immediately. Initially, the company receives an advance equal to approximately 10% of the total investment amount. As the project progresses and successfully completes each planned stage, additional funding is released in amounts corresponding to the value of each completed phase.

This approach allows investors to protect themselves against technological failures or project-related errors. In the event of difficulties or technical problems, subsequent funding tranches are released only after corrective measures have been implemented and the project stage has been successfully completed.

Distribution of Company Shares

Upon formation of the company, the project authors receive 50% of the company's shares.

The private investor contributing USD50,000 receives 15% of the shares.

The remaining 35% of shares are allocated as follows:

- Technology incubator – 25%
- Employees who make the most significant contribution to project implementation – 10%

Return on Investment

Repayment of invested funds begins only after the project generates its first commercial profits and is limited to no more than 5% of annual profits.

In the event that the project is unsuccessful and unable to generate commercial returns, the invested funds are not reimbursed.

To attract investors, governmental and public authorities should establish appropriate incentives. One of the most significant incentives would be the exemption of newly established companies from corporate profit taxes for a period of at least ten years following the generation of their first profit.

All of the above represents a conceptual proposal. In practice, alternative organizational and implementation models may emerge depending on specific circumstances.

Expansion into International Markets

Let us assume that the project proves successful and economically efficient.

In such a case, additional opportunities arise for commercial implementation, including expansion into international markets and, under favorable conditions, the eventual listing of the company on stock exchanges in the United States or European countries.

The mechanisms by which this may be accomplished within the framework of existing laws and market conditions will be discussed in our next article.

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submitted 08.06.2026;
accepted for publication 22.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-214-218



TECHNOLOGY INCUBATOR AS AN ELEMENT OF THE INNOVATION ECOSYSTEM. (The Role of a Technology Incubator in the Innovation Ecosystem of Industrial and Agricultural Production Development)

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Cite: Malyeryk Kh. (2026). *Technology Incubator as an Element of the Innovation Ecosystem. (The Role of a Technology Incubator in the Innovation Ecosystem of Industrial and Agricultural Production Development)*. Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-214-218>

Abstract

This article examines the role of technology incubators as essential components of the innovation ecosystem, facilitating the effective transformation of scientific ideas, engineering developments, and promising technological solutions into commercially viable products and services. Particular attention is given to the organizational, technological, and economic mechanisms involved in creating a favorable innovation environment that promotes the accelerated development of startups and the implementation of new technologies in industrial and agro-industrial production.

The publication provides an analysis of the formation and development of technology incubators as specialized structures supporting innovation activities. The study explores the fundamental principles governing their operation, including expert project support, the integration of scientific potential with industrial resources, the attraction of investment capital, and the creation of conditions necessary for the commercialization of advanced developments.

Special emphasis is placed on the significance of technology incubators for the development of industrial and agricultural production, the enhancement of enterprise competitiveness, the implementation of modern digital technologies, and the formation of sustainable innovation ecosystems. The article also analyzes opportunities for cooperation between technology incubators, research institutions, industrial enterprises, investment organizations, and governmental development agencies.

The study highlights that technology incubators represent an effective instrument for supporting innovative entrepreneurship and fostering the emergence of new high-technology sectors. By accelerating the transfer of scientific and technological achievements into practical applications, technology incubators contribute to the long-term innovative development of industrial and agro-industrial complexes and promote sustainable economic growth.

Keywords: *Technology incubator; Innovation ecosystem; Effective implementation; Innovative development model of industrial and agricultural production; Ecosystem infrastructure*

framework; Quantum computing; Augmented reality visualization; Testing laboratories; Laws of technical system evolution; Standardization; Technology transfer

Introduction

The laws and practices governing the comprehensive development of integrated technical systems and supersystems under conditions involving the application of quantum computers and their simplified modifications, combined with embedded elements of artificial intelligence and artificial neural networks, represent an increasingly important area of scientific and technological research.

Due to the critical role played by analytical efficiency in determining the success of innovative initiatives and the appropriateness of patent and licensing strategies for projects incorporating highly novel technical and software solutions, investors and managers of new, pioneering projects frequently encounter a shortage of computational performance and analytical depth required for the real-time processing and modeling of complex innovation-related processes using conventional computing systems.

Information regarding the successful testing of a quantum computer developed by Google Corporation has provided a well-founded basis for optimism concerning progress in this field.

According to the generally accepted definition, a quantum computer is a computational device that utilizes the phenomena of quantum mechanics for data transmission and processing.

Unlike conventional computers, which operate using bits capable of assuming either a value of 0 or 1, quantum computers operate using qubits, which can simultaneously represent both 0 and 1. Theoretically, this capability enables the simultaneous processing of all possible states of systems at various hierarchical levels, including both subsystems and supersystems, thereby providing substantial advantages over traditional computing architectures.

Furthermore, the absence of analytical tools of this type significantly increases the cost structure of innovative projects, as extensive computational modeling, high-speed iteration of alternative solutions, and comprehensive analytical evaluation of their feasibility and effectiveness become necessary.

At the same time, the laws governing the evolution of technical systems formulated within TRIZ (Theory of Inventive Problem Solving) are no longer capable of fully reflecting the diversity of functions, tasks, and characteristics associated with modern multifunctional innovation objects. Considering the emergence of numerous new factors influencing innovative systems, these laws require reformulation and integration with the principles governing the development of commercial organizations and the commercialization of innovative ideas.

Such formulations should be based on empirical data and the results obtained from quantum-computing research while taking into account the nature of the fundamental contradictions identified within innovative systems and technologies.

The dialectical approach based on contradiction analysis, which formed the foundation of ARIZ (Algorithm for Inventive Problem Solving), was subsequently modified through the introduction of concepts such as “technical contradiction” and “physical contradiction.” These concepts were originally intended to facilitate modeling under conditions where existing computer systems lacked sufficient computational power and processing speed to support real-time simulation of complex innovation processes.

However, the introduction of these additional concepts partially distorted the original meaning of dialectical contradiction as defined within dialectical logic. As a result, significant difficulties emerged when attempting to identify and resolve contradictions within real-world inventive and innovation-oriented tasks using ARIZ methodologies, primarily due to limitations in computational resources and the inability to perform sufficiently deep and comprehensive process modeling.

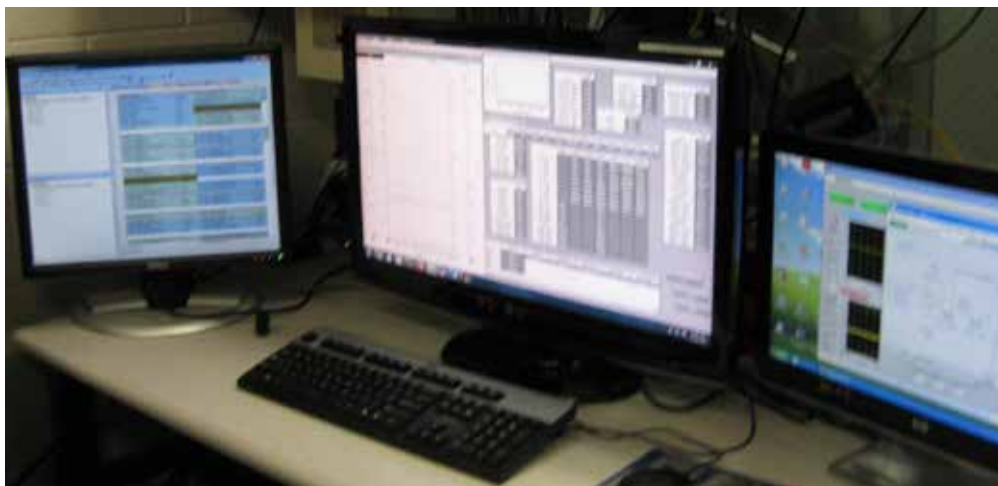
Particular attention should be devoted to a fundamentally important question: what should be considered a genuine inventive innovation problem?

From the perspective of investors and project managers, effective analytical assessment of project development requires a clear

understanding of the relationship between the formulation of an inventive problem and its impact on the commercialization of the resulting invention. An accurate or inaccurate formulation of project objectives and inventive tasks, especially in the absence of step-by-step analytical modeling, may lead to uncertainty regarding a fundamental issue: whether the resulting technical solution can be reliably protected against unauthorized copying and imitation.

The search for answers to these and many other related questions has become an essential component of the modern methodology for developing innovation strategies, establishing effective commercialization pathways, and ensuring reliable patent protection and licensing of inventions created throughout all stages of innovation project development.

Figure 1.



The following provides a brief overview of the organizational structure, activities, scientific collaborations, and industrial partnerships of existing technology incubators.

Government Structures Supporting Innovation Development

Technology incubators are government-supported organizations established to facilitate the development, financing, and commercialization of innovative projects, helping them successfully transition into independent participants within competitive markets.

Technology incubators operate under the supervision of the Ministry of Industry and Trade and, to a certain extent, the Ministry of Agriculture.

Both ministries maintain dedicated budgets for supporting the activities of technology incubators. Separate funding mechanisms are allocated for direct investment in innovative projects and for financing project management and administrative activities.

Chief Scientist of the Ministry of Industry and Trade

The position of Chief Scientist, together with the corresponding department, has been established to provide methodological support to technology incubators and to oversee the selection, evaluation, and monitoring of projects conducted within the incubator system.

The Office of the Chief Scientist includes divisions and groups of highly qualified experts, both permanent and external, who carry primary responsibility for evaluating innovative projects and recommending them for inclusion in the thematic development programs of technology incubators.

Each expert supervises several projects located in different incubators and serves as a key participant in the monitoring, evaluation, and financing of these projects.

Export Institute

The Export Institute provides projects within technology incubators with comprehensive methodological, informational, and consulting support.

In addition, the Export Institute offers substantial competitive grants, often reaching approximately USD120,000, for projects demonstrating significant export potential.

The Institute also assists in the preparation of promotional materials, prospectuses, technical documentation, and marketing publications, while actively supporting the introduction of newly developed innovative products into international markets.

National Standards Institute

Compliance with international standards is one of the fundamental prerequisites for successful commercialization and market

entry of innovative products. Consequently, a well-established practice of continuous co-operation has developed between technology incubators and the National Standards Institute.

An equally important factor is the exceptionally high quality of technical evaluation, certification, testing, and performance verification conducted within the Institute's laboratories. These assessments are performed using advanced testing and measurement equipment, ensuring objective and reliable validation of the technical characteristics of innovative products before their commercialization and market deployment.

Figure 2.



Commercial Testing Laboratories

In addition to the National Standards Institute, there also exists an extensive network of commercial testing laboratories capable of conducting testing and certification of innovative products in accordance with regulatory standards and technical requirements that may not be recognized or adopted in certain jurisdictions, including European countries.

Furthermore, standards corresponding to internationally accepted measurements,

technical specifications, weight systems, dimensional requirements, and other regulatory parameters are not always uniformly implemented in the countries to which innovative products are intended to be exported.

To address this challenge and to obtain reliable information regarding compliance with local regulatory requirements during the product development stage, technology incubators actively utilize the advantages

provided by cooperation with commercial testing laboratories.

Such cooperation enables developers and project managers to identify potential compliance issues at an early stage, optimize product specifications for target markets, reduce certification risks, accelerate market entry procedures, and improve the

overall competitiveness of innovative products in international markets.

As a result, commercial testing laboratories serve as an important component of the innovation ecosystem, complementing the activities of governmental standardization institutions and contributing to the successful commercialization and international expansion of innovative technologies and products.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-219-228



**FUEL MIXTURE ACTIVATION TECHNOLOGIES
FOR CUSTOMS FACILITY INFRASTRUCTURE
(Integrated fuel mixture activation technology by
dissolving combustible gas (methane, propane, or
a propane–butane gas mixture) in diesel fuel or gasoline
prior to its injection into the combustion chamber
within the infrastructure of a customs facility)**

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Cite: Mehei A. (2026). *Fuel mixture activation technologies for customs facility infrastructure. (Integrated fuel mixture activation technology by dissolving combustible gas (methane, propane, or a propane–butane gas mixture) in diesel fuel or gasoline prior to its injection into the combustion chamber within the infrastructure of a customs facility). Austrian Journal of Technical and Natural Sciences 2026, No 5–6.* <https://doi.org/10.29013/AJT-26-5.6-219-228>

Abstract

This article examines integrated fuel mixture activation technology and the design of a dedicated activation device intended to improve the preparation of fuel mixtures prior to their injection into the combustion chamber. Particular attention is devoted to the engineering principles of complex fuel activation, the optimization of combustion processes, and the enhancement of engine performance without requiring modifications to the combustion chamber or its operating conditions.

The publication analyzes the principal technical advantages of the proposed technology, including external monitoring and regulation of the fuel activation process, increased concentration of dissolved combustible gases within the fuel mixture, improved pressure retention in fuel microdroplets, enhanced air distribution following injection, shortened activation cycles, and the capability of processing multicomponent fuel mixtures containing both organic and inorganic constituents, as well as functional additives. The study further considers the advantages of achieving these improvements without additional external energy sources while maintaining compatibility with existing engine systems.

Special emphasis is placed on the commercial potential of the integrated fuel activation technology. The article discusses opportunities for reducing fuel consumption, increasing the effective octane rating of fuel mixtures, improving engine operating characteristics, lowering equipment manufacturing and installation costs, enabling the utilization of low-calorific fuels and blended fuel compositions, and combining fuel activation, dissolution, and mixing processes within a single technological system.

The publication further examines the integration of the proposed fuel activation technology with advanced combustion concepts, including Homogeneous Charge Compression Ignition (HCCI). Particular attention is devoted to improvements in combustion efficiency, reduction of combustion temperatures and harmful emissions, enhancement of fuel atomization and combustion kinetics, increased heat release performance, support for near-adiabatic combustion conditions, and the implementation of external monitoring and remote control technologies for fuel preparation prior to injection. The study concludes that the proposed integrated activation approach offers significant potential for improving the efficiency, environmental performance, and commercial competitiveness of next-generation internal combustion engine technologies.

Keywords: *Supersystem of the infrastructure and ecosystem of the customs workspace and its transition into an advanced smart integrative combined system; Subsystem of the infrastructure and ecosystem of the customs workspace and its transition into an advanced smart integrative combined system; Transformation of complex constituent parts, supersystems, and subsystems of infrastructure; Metallization in a directed electrolyte flow; Emergence of the edge effect; Production of electronic printed circuit boards for modules and control and monitoring units of a smart mobile home; Engineering, technology, and design in the formation of structural systems and infrastructure inherent in smart manufacturing and a smart mobile home and its equivalents*

Contents

- Introduction
- Description of the fuel mixture activation process
- Possible fuel mixture components
- Description of design options for the integrated fuel mixture activation device
- Advantages of the proposed fuel mixture activation process resulting from the design features and operating characteristics of the proposed activation device
- Previously tested technologies that preceded the development of the integrated fuel mixture activation technology and their positive contribution to the performance characteristics and output parameters of the proposed technology
- Characteristics of the integrated fuel mixture activation technology
- Sequential description of the technological stages of the integrated fuel mixture activation process
- Schematic diagram of the devices and components comprising the fuel system of an automobile or aircraft utilizing the integrated fuel mixture activation technology
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- Operating characteristics of the activated fuel mixture prior to its injection into the combustion chamber
- Operating characteristics of the fuel mixture after injection into the combustion chamber
- Methods for regulating the principal operating characteristics of the activated fuel mixture; capability for remote control of the regulation process; principal control parameters; feedback mechanisms
- Principal operating parameters of the integrated activated fuel mixture that determine its advantages over existing fuel preparation technologies prior to combustion
- Description of the injection process of the integrated activated fuel mixture into the combustion chamber; advantages resulting from the injection of the activated fuel mixture
- Predicted and calculated characteristics of the combustion process of the integrated activated fuel mixture
- Technical and commercial advantages of applying the integrated fuel mixture activation technology

Introduction

An integrated technology for influencing the fuel mixture prior to its injection into the combustion chamber is proposed.

The proposed technology is based exclusively on well-established and repeatedly verified physical principles and laws embodied in a compact integrated engineering design.

The proposed technology and the device implementing it can be applied to existing internal combustion engine systems without any modification of their design or operating principles.

The proposed technology utilizes only well-known and widely used combustible fuel components and their combinations.

The proposed technology also enables the integrated use of both conventional and newly formed fuel components generated during the activation and dissolution processes, which are subsequently mixed with the primary fuel components through the operating characteristics of the proposed activation device.

A universal and flexible technology is proposed, allowing multiple technological configurations to be implemented within a single activation device.

The proposed technology incorporates a control, monitoring, and regulation system based on a minimal number of monitored and controlled process parameters that have a direct relationship with and influence on both the efficiency of the fuel mixture activation process and the efficiency of fuel combustion in achieving the required energy and environmental performance.

Description of the fuel mixture activation process

The objectives of the fuel mixture activation process are to increase the octane or cetane rating of the fuel mixture supplied to the combustion chamber during each operating cycle; reduce fuel consumption; increase the specific calorific value of the fuel; improve combustion uniformity; increase combustion completeness; reduce the concentration of toxic exhaust gases; maximize the energy released during combustion; reduce vibration and aerodynamic noise generated during combustion; provide reliable remote control of both the combustion process and the activation process prior to fuel injection; and ensure that all monitored and controlled parameters directly influence the combustion performance within the combustion chamber.

The technological sequence of the fuel mixture activation process is as follows.

The primary fuel component, representing the dominant proportion of the fuel mixture, is stored in a hermetically sealed fuel tank equipped with continuously operating sensors measuring viscosity, density, temperature, and fuel level. Signals from these sensors are transmitted to the process control system.

The control system operates a fuel pump with regulated and monitored flow rate and pressure. The pump delivers the liquid fuel component through the fuel pipeline connected to the inlet of the integrated fuel mixture activation device.

Within the first section of the activation device, the fuel stream supplied under pressure is transformed, accelerated through a series of microchannels, and brought to a highly turbulent flow condition.

In the second section of the activation device, a pressurized stream of compressed combustible gas is introduced into the highly turbulent liquid flow. Owing to its high linear velocity, the gas stream creates a localized low-pressure region at the point of entry into the liquid stream. This localized pressure reduction facilitates the penetration of the compressed combustible gas into the liquid fuel, despite the incompressible nature of the liquid phase.

At the interface between the gaseous and liquid media, the localized low-pressure region generates a pseudo-boiling volume that subsequently develops into a foam-like structure. Under the combined pressure of the system, this foam advances toward the combustion chamber. By the end of its travel, the combustible gas becomes completely dissolved within the liquid fuel, and the resulting fuel mixture containing dissolved combustible gas is injected directly into the combustion chamber.

1.1. Possible fuel mixture components

- 1.2. The components of the fuel mixture that undergo mixing and activation within the fuel mixture activation device may be classified into several groups.
- 1.3. The principal and dominant group of components consists of liquid hydrocarbons, including gasoline, diesel fuel, ethanol, and kerosene.

- 1.4. An auxiliary group of liquid hydrocarbon components that may also be used in the fuel mixture includes synthetic gasoline, biologically derived hydrocarbons, and liquefied gas.
- 1.5. An auxiliary group of liquid fuel mixture components consists of inorganic liquids, such as purified water, synthetic water, and synthetic water generated directly within the engine by means of a heat pipe.
- 1.6. As an alternative inorganic liquid fuel component, water saturated with coal or carbon dust may also be utilized.
- 1.7. As a gaseous fuel component, compressed combustible gas or aerosols based on mixtures of combustible gases with various hydrocarbons obtained through the integrated filtration of combustible gas prior to its delivery to the compressor may be employed.
- 1.8. Description of design options for the fuel mixture activation device
- 1.9. The integrated fuel mixture activation device consists of two principal operating sections.
- 1.10. The first section, in the direction of fuel mixture flow, is the hydraulic section, followed by the pneumatic section.
- 1.11. The hydraulic section incorporates a design that includes a system for intensive vortex mixing of the liquid fuel mixture components. This process is accomplished without the use of additional energy sources and utilizes the same structural elements whose primary function is to increase the turbulence level of the flowing medium.
- 1.12. The pneumatic section is intended to increase the flow velocity of the compressed combustible gas, introduce this gas stream into the turbulent flow of the liquid fuel components, transform the integrated stream of all fuel components into a foam-like structure, and discharge the integrated activated fuel mixture containing dissolved combustible gas into the fuel pipeline.
- 1.13. The integrated fuel mixture activation device is installed within the fuel pipeline and is provided with a hermetically sealed, high-pressure-resistant housing equipped with fastening elements for connection to the fuel pipeline.
- 1.14. Advantages of the fuel mixture activation process resulting from the design features and operating characteristics of the activation device.
- 1.15. The principal advantage of the integrated fuel mixture activation device is that the activation process within both of its primary operating sections is based on the Bernoulli principle.
- 1.16. The channel through which the fuel mixture components flow is formed by transforming the cylindrical fuel pipeline into an annular flow channel of larger diameter with a relatively small gap between the concentric cylindrical surfaces while maintaining an equivalent total flow cross-sectional area. This configuration creates preliminary conditions for the formation of turbulent flow regions and promotes the accelerated dissolution of combustible gases within liquid hydrocarbons.
- 1.17. The localized regions in which the critical physical phenomena associated with the Bernoulli effect are generated are arranged sequentially along the direction of fuel mixture flow. As a result, the liquid fuel components are accelerated, vortex turbulence zones are created, and streams of compressed combustible gas or combustible gas mixtures are introduced into these regions at high pressure and velocity.
- 1.18. The entire process takes place within a hermetically sealed, high-strength housing, making it possible to substantially increase the pressure of the combustible gas. Upon interaction with the incompressible liquid fuel components, the compressed gas forms small, high-pressure gas bubbles within the liquid phase. Because the activation process occurs within a closed volume, the position of these gas bubbles and their distribution relative to the liquid fuel components remain stable throughout the residence time of the fuel mixture within the activation device and the fuel pipeline until its injection into the combustion chamber.

- 1.19. Consequently, the principal beneficial properties of the integrated activated fuel mixture are generated by the distinctive structural characteristics of the integrated fuel mixture activation device itself.
- 1.20. Previously tested technologies that preceded the development of the integrated fuel mixture activation technology and their contribution to its performance characteristics.
- 1.21. The development of the integrated fuel mixture activation technology was preceded by technologies for the aerodynamic capture and handling of objects in various media, including gaseous and liquid environments.
- 1.22. During the development of aerodynamic gripping technologies, aerodynamic grippers were created that provided approximately a tenfold increase in lifting capacity while maintaining the same geometric dimensions and energy consumption.
- 1.23. The highly effective methods for generating localized low-pressure zones, together with the engineering tools developed for producing such regions, were substantially modified by the inventors of the earlier technologies and subsequently incorporated into the integrated fuel mixture activation technology.
- 1.24. Characteristics of the integrated fuel mixture activation technology prior to injection into the combustion chamber
- 1.25. The originality of the integrated fuel mixture activation technology lies in its use of the Bernoulli principle to intensify all processes associated with the transformation, dissolution, and mixing of the various liquid and gaseous components of the fuel mixture.
- 1.26. A second aspect of its originality and effectiveness is the sequential, stage-by-stage creation of technological conditions that enable the beneficial effects of the Bernoulli principle to be utilized in achieving the desired output characteristics of the activated fuel mixture.
- 1.27. A third aspect of the technology's effectiveness lies in the combination of the structural advantages of the activation

device with the operational benefits derived from applying the Bernoulli principle throughout the activation process.

Sequential description of the technological stages of the fuel mixture activation process

The **first technological stage** consists of preparing the dominant liquid hydrocarbon component before it enters the fuel pump. At this stage, the principal parameters of the component, including density, viscosity, temperature, and fuel level within the storage tank, are continuously monitored.

The **second technological stage** consists of comparing the signals received from the sensors with the statistical model stored in the processor. If the measured parameters correspond to the statistical model, the processor issues a command to activate the fuel pump.

The **third technological stage** consists of starting the fuel pump and delivering the liquid fuel into the fuel pipeline. During this stage, the pressure within the fuel pipeline is measured and transmitted to the processor. If the measured pressure corresponds to the specified value, the processor issues a command to activate the compressor. If the pressure deviates from the prescribed value, the operating parameters of the fuel pump are adjusted until the required pressure is achieved, after which the compressor is activated.

The **fourth technological stage** is performed simultaneously with the fifth stage. It consists of activating the compressor and monitoring the pressure of the compressed combustible gas within the gas pipeline. If the pressure reaches the specified value, the processor authorizes continuation of the activation process. If the pressure differs from the prescribed level, the compressor operating parameters are adjusted until the required pressure is achieved. Since all geometric parameters of the gas pipeline remain constant, the gas pressure determines both the flow rate and the velocity of the compressed combustible gas throughout the pneumatic section of the fuel mixture activation device.

The **fifth technological stage**, performed simultaneously with the fourth stage, consists of transforming the liquid fuel stream within the hydraulic section of the

activation device and increasing its level of turbulence.

The **sixth technological stage** is an optional stage applied when the fuel mixture contains a second liquid fuel component. During this stage, which is also performed simultaneously with the fifth stage, the second liquid component is drawn into the localized low-pressure zone and intensively mixed with the primary fuel component.

The **seventh technological stage** constitutes the principal stage of the activation process. Its primary objective is to saturate the liquid fuel component with dissolved combustible gas, convert the resulting mixture into a foam-like structure, and subsequently restore the system pressure to its original operating level.

The **eighth technological stage** consists of monitoring the dielectric permittivity of the integrated activated fuel mixture. If the measured dielectric permittivity corresponds to the statistical model, the processor issues a command to inject the activated fuel mixture into the combustion chamber. If the measured value differs from the specified parameter, both the fuel pump pressure and the compressor pressure are adjusted until complete agreement between the measured parameters and the statistical model is achieved, after which the processor authorizes fuel injection.

Schematic arrangement of the devices and components comprising the fuel system of an automobile or aircraft utilizing the integrated fuel mixture activation technology

The integrated fuel mixture activation device may be incorporated into the fuel system of any automobile, aircraft, or other vehicle equipped with an internal combustion engine.

The essential components of the system include fuel component reservoirs, fuel pipelines, a fuel pump, a compressor, the integrated fuel mixture activation device with a storage vessel for liquefied combustible gas, and a system of sensors and monitoring devices.

An optional subsystem consists of a real-time resonant monitoring system for measuring the dielectric permittivity of the fuel mixture immediately prior to its injection into the combustion chamber.

Operating procedure of the fuel mixture activation device as applied to the fuel system of an automobile or aircraft engine

Operating characteristics of the activated fuel mixture prior to its injection into the combustion chamber

The integrated activated fuel mixture produced by the two-stage mixing, turbulence enhancement, and foaming device possesses the following principal characteristics prior to injection into the combustion chamber.

The integrated activated fuel mixture may contain combinations of liquid organic fuel components and combustible gases dissolved within them, mixed in various proportions such that components present at lower concentrations are uniformly distributed throughout the volume of the dominant fuel component.

The integrated activated fuel mixture may also contain combinations of organic and inorganic fuel components mixed in various proportions so that the inorganic components are uniformly distributed throughout the organic phase.

Following completion of the activation cycle, the integrated activated fuel mixture constitutes at least a two-component liquid system in which numerous dissolved combustible gas molecules are uniformly distributed throughout the liquid phase while remaining under the pressure of the fuel pipeline. These dissolved gas molecules retain the kinetic energy imparted by the highly developed turbulent flow generated during the activation process.

Operating characteristics of the activated fuel mixture after its injection into the combustion chamber

One of the most important characteristics of the integrated activated fuel mixture is its octane rating, which serves as an indicator of resistance to engine knock. For premium gasoline produced by catalytic reforming, this conventional indicator is approximately 86. The anticipated octane rating of activated gasoline containing combustible gas dissolved at a concentration of approximately 10% by the mass of the liquid hydrocarbon is expected to reach approximately 120.

The technical capabilities of the integrated fuel mixture activation device also make it possible to produce gasoline–benzene mixtures, where benzene possesses an octane rating of approximately 113. Such a modification is expected to increase the octane rating of the activated fuel mixture to approximately 125.

The activated fuel mixture exhibits a mass burning rate approximately one order of magnitude greater than that of conventional fuel mixtures. The mass burning rate is defined as the quantity of fuel consumed per unit area of the combustion front per unit time.

The activated fuel mixture also exhibits sufficiently high combustion reaction rates and heat release rates – the quantity of thermal energy released per unit time – to maintain stable combustion even under reduced-temperature operating conditions.

Furthermore, the activated fuel mixture satisfies the conditions required for adiabatic combustion, whereby the combustion reaction is completed before significant heat exchange occurs between the reaction volume and the surrounding environment, thereby minimizing thermal and energy losses.

Methods for regulating the principal operating characteristics of the activated fuel mixture; capability for remote control and regulation of the fuel mixture activation process; regulated fuel mixture parameters; feedback during monitoring and regulation

The integrated fuel mixture activation technology incorporates two principal technological parameters that determine both the degree of activation and the overall effectiveness of the process.

The first parameter is the pressure within the fuel pipeline generated by the fuel pump. Since the internal diameter of the fuel pipeline remains constant, the pressure within the pipeline determines both the flow velocity and the volumetric flow rate of the liquid fuel. These direct and derived parameters determine the turbulence level of the flowing medium, which, in turn, governs the degree of turbulence generated within the hydraulic section of the integrated fuel mixture activation device, whose geometric parameters remain constant. Consequently, by regulating the

pressure within the fuel pipeline, it is possible to control the activation process occurring in the hydraulic section of the device. Pressure signals transmitted to the control processor provide an accurate assessment of the condition of the fuel mixture prior to its injection into the combustion chamber and enable automatic adjustment of the fuel pressure to restore the required operating conditions.

The second parameter is the pressure within the pipeline supplying compressed combustible gas to the pneumatic section of the integrated fuel mixture activation device, where the gas is dissolved within the liquid hydrocarbon fuel.

This parameter is considered the most important because the pressure of the gaseous working medium – primarily methane or propane – determines the flow velocity of the compressed combustible gas. This velocity governs several fundamental factors upon which the effectiveness of the activated fuel mixture depends.

The flow velocity of the compressed combustible gas determines the following principal characteristics of the integrated activated fuel mixture:

- the proportional relationship between the dissolved gaseous phase and the liquid phase of the fuel mixture;
- the uniformity of distribution of the dissolved gaseous phase throughout the volume of the liquid fuel component.

Accordingly, the pressure of the compressed combustible gas supplied to the integrated fuel mixture activation device determines the magnitude and effectiveness of the principal properties and characteristics of the activated fuel mixture. Regulation of this pressure makes it possible to control the principal operating characteristics of the fuel mixture.

Pressure measurements also provide reliable real-time feedback reflecting the condition and properties of the activated fuel mixture throughout the activation process.

Principal operating parameters of the integrated activated fuel mixture providing advantages over existing fuel preparation technologies

The principal operating parameters of the integrated activated fuel mixture include the

concentration of dissolved combustible gas within the fuel mixture and the specific active contact surface area of the fuel mixture following its injection into the combustion chamber.

Prior to injection into the combustion chamber, the condition of the integrated activated fuel mixture is characterized by the following parameters:

- the quantity of dissolved combustible gas per unit volume of the fuel mixture;
- the ratio between the quantity of dissolved combustible gas and its volumetric content within the fuel mixture;
- the specific density of a unit volume of the activated fuel mixture;
- the specific contact surface area per unit volume of the activated fuel mixture.

Where several fuel components are combined during the integrated activation process, the modified octane rating or cetane rating of the resulting fuel mixture becomes an additional important indicator of its performance.

Description of the injection process of the integrated activated fuel mixture into the combustion chamber and the advantages achieved during injection

The injection process of the integrated activated fuel mixture possesses characteristics that are not typical of conventional fuel mixtures.

Within the integrated activated fuel mixture, the internal pressure may reach considerable values. While the mixture remains inside the activation device and within the fuel pipeline upstream of the combustion chamber, this condition remains stable.

Following injection into the combustion chamber, the volume occupied by the injected fuel charge expands. The excess pressure within the spray plume fragments the fuel stream into microdroplets, while the dissolved combustible gas, possessing a lower boiling point than the liquid fuel components, simultaneously ruptures the liquid envelope surrounding the droplets. This envelope is dispersed into a finely atomized three-dimensional structure exhibiting a rel-

atively uniform distribution throughout the combustion chamber prior to ignition.

This volumetric distribution of the activated fuel mixture provides the following advantages:

- high combustion velocity;
- a high degree of combustion completeness;
- a uniform combustion front;
- high heat release within a short period of time;
- a short overall combustion cycle;
- high specific energy output resulting from fuel combustion;
- low levels of micro-vibration and micro-shock during combustion;
- reduced concentrations of toxic combustion products in the exhaust gases;
- lower combustion temperatures, resulting in reduced emissions of toxic exhaust gases.

Predicted and calculated characteristics of the combustion process of the integrated activated fuel mixture

The principal performance characteristics used to evaluate the combustion process of the integrated activated fuel mixture include the combustion rate, flame propagation velocity, combustion completeness, specific calorific value during combustion, and the concentration of toxic substances within the combustion products.

Additional performance characteristics include the mass burning rate, linear burning rate, combustion-front surface area corresponding to a unit volume of the fuel mixture, combustion reaction rate, and heat release power.

Auxiliary performance characteristics include the turbulent flow parameters of the fuel mixture during its injection into the combustion chamber. These turbulence-induced pulsations intensify heat transfer and mass transfer within the flame, distort and fragment the combustion front, expand the combustion reaction zone, and thereby produce a substantial acceleration of the combustion process.

The turbulent flame propagation velocity of the integrated activated fuel mixture is expected to exceed the corresponding values

observed in conventional fuel mixtures by several tens of times.

Technical and commercial advantages of applying integrated fuel mixture activation prior to injection into the combustion chamber

The application of integrated fuel mixture activation in combination with the design of the integrated fuel mixture activation device provides, in comparison with existing fuel preparation systems and technologies intended for preparing the fuel mixture prior to its injection into the combustion chamber, a number of technical advantages that directly determine significant commercial benefits.

The principal technical advantages include:

- the ability to perform fuel mixture activation prior to injection into the combustion chamber without any modification to the combustion chamber design or its operating conditions;
- the ability to achieve a high level of kinetic energy during the activation process without the use of additional external energy sources;
- the ability to perform continuous monitoring and regulation of the activation process without accessing the combustion chamber, using only standard external monitoring instruments and standard external control methods for adjusting the required process parameters;
- the ability to increase the specific concentration of dissolved combustible gas within the fuel mixture;
- the ability to increase and maintain high pressure within the microdroplets of the fuel mixture during the injection process;
- the ability to achieve highly uniform air distribution throughout the fuel mixture after injection;
- the ability to substantially reduce the duration of the activation cycle;
- the ability to process multicomponent fuel mixtures within a single activation device;
- the ability to activate fuel mixtures containing both organic and inorganic

components within the same activation device;

- the ability to activate fuel mixtures containing alloying or functional additives within a single integrated activation system.

The principal commercial advantages of the integrated fuel mixture activation technology include:

- reduced fuel consumption during the combustion process;
- increased octane or cetane rating of the fuel mixture;
- improved operational characteristics of internal combustion engines;
- significant reduction in the manufacturing cost of the integrated fuel mixture activation device;
- low installation costs for integrating the activation device into vehicles;
- the capability of utilizing low-calorific fuels and blended fuel compositions in internal combustion engines;
- the capability of performing fuel activation, dissolution, and mixing of fuel components simultaneously within a single integrated device.

The combination of the integrated fuel mixture activation technology with advanced internal combustion engine cycle modification technologies currently under development, including **Homogeneous Charge Compression Ignition (HCCI)** technology, is expected to provide the following additional advantages:

- increased concentration of air or other oxidizing agents within the fuel mixture;
- reduced combustion temperature within the combustion chamber;
- reduced or completely eliminated concentrations of toxic exhaust gases;
- increased atomization fineness of the fuel spray during injection into the combustion chamber;
- an approximately 100- to 1,000-fold increase in the active surface area of the fuel mixture following injection into the combustion chamber;
- increased combustion completeness of the fuel mixture;
- increased heat release power;

- establishment of conditions favorable for adiabatic combustion;
- increased mass burning rate;
- increased linear flame propagation velocity;
- increased combustion reaction rate;
- reduced vibration and detonation during the engine operating cycle;
- complete remote monitoring of fuel mixture parameters outside the combustion chamber;
- remote control of the fuel preparation process prior to injection into the combustion chamber, based on accurate real-time measurements of the actual concentration of dissolved combustible gas within the fuel mixture immediately before injection.

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submitted 15.06.2026;
accepted for publication 29.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-229-240



**THE IMPACT OF DIGITAL TECHNOLOGIES INCORPORATING
ARTIFICIAL INTELLIGENCE ON THE INDUSTRIAL DESIGN PROCESS
(The impact of digital technologies incorporating elements
of artificial intelligence on the industrial design process,
as well as on the form, structure, and characteristics of
modern technical systems of varying levels of complexity)**

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Cite: Nedelcu Mircea. (2026). *The impact of digital technologies incorporating artificial intelligence on the industrial design process. (The impact of digital technologies incorporating elements of artificial intelligence on the industrial design process, as well as on the form, structure, and characteristics of modern technical systems of varying levels of complexity).* Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-229-240>

Abstract

The article examines the impact of digital technologies incorporating artificial intelligence elements on industrial design and the evolution of technical systems. Transformations in design processes enabled by CAD systems (SolidWorks), virtual simulation, and TRIZ methodologies are analyzed. The laws governing the development of technical systems, Gudolin's classification, and the concept of the Ideal Final Result are reassessed in the context of digitalization. Using examples of liquid homogenization devices, the integration of digital modeling, new materials, and intelligent control systems is demonstrated. It is concluded that AI is becoming an active component of the innovation process, reshaping approaches to engineering design and patenting of technical solutions.

Keywords: *Technologies; Smart technologies; Smart manufacturing technologies; Current level of manufacturing process development; Classical methods of processing raw materials, digital technologies, and new composite materials; Non-contact electromagnetic resonance testing; High-speed metallization technology; The process of achieving the ideal final result; Auxiliary materials and tools whose combined use makes it possible to approach the achievement of an ideal final result; Globalization of manufacturing processes; The expansion of areas of application follows a fan-shaped pattern and gradually spreads to numerous related processes, including both manufacturing and all auxiliary operations and processes*

Introduction:

Until relatively recently, the majority of inventions were characterized by a rather lo-

calized scope, and the positive effects resulting from their implementation could be identified and evaluated with relative ease.

Today, due in large part to the significantly expanded capabilities of modern computer-aided design and engineering software, the outcomes of the design process make it possible to assess and classify the originality, novelty, and innovative value of newly developed technical systems with a substantially higher degree of accuracy, regardless of their level of complexity.

The integration of advanced digital technologies, including systems incorporating elements of artificial intelligence, machine learning algorithms, simulation environments, and virtual engineering platforms, has fundamentally transformed the processes of industrial design, engineering analysis, and technological innovation. Modern design tools allow specialists not only to develop complex technical systems but also to predict their operational characteristics, evaluate alternative design solutions, optimize resource utilization, and identify potential deficiencies

long before physical prototypes are manufactured.

As a result, the process of creating innovative technical systems has become increasingly multidisciplinary, combining engineering, mathematical modeling, digital simulation, economics, logistics, and data analysis into a unified technological framework. This transformation has significantly increased the effectiveness of innovation activities while simultaneously raising the standards applied to the evaluation of novelty, technical originality, and practical applicability of engineering solutions.

Under these conditions, the influence of artificial intelligence-enabled digital technologies extends far beyond traditional design activities, affecting the structure, functionality, operational characteristics, and overall evolution of modern technical systems across a wide range of industrial sectors.

Figure 1. *Presents a design model of a device intended for the real-time homogenization of fuel mixtures*



As can be seen from the figure, the design process also simulates the characteristics arising from the selection of structural materials, as well as the properties of protective and decorative coatings applied during the design stage through the capabilities and modeling tools of the Solid Works software family.

The design process makes it possible to create entire families of technical systems, thereby providing additional time-saving opportunities and reducing the overall cost of engineering and design activities.

Today, as computer-aided engineering methods have become deeply integrated into

the process of technical and technological decision-making – particularly those associated with the SolidWorks software family, which can reasonably be regarded as incorporating elements of artificial intelligence – the number of factors, characteristics, and developmental pathways associated with a technical solution, extending ultimately to the level of a technical supersystem, has become extremely significant. This creates a need for a systematic correspondence between technical solutions and the definitions, classifications, and identification methods applicable to the entire hierarchy of engineering sys-

tems, ranging from local technical solutions with unregulated technical and technological relationships (subsystems) to highly complex conglomerates of interconnected technical solutions forming supersystems.

It should be acknowledged that one of the first specialists to undertake the optimization of classifications for such categories of technical solutions was *Oleksandr Gudolin*, whose publications introduced a systematic approach to this subject by combining the methodology and principles of classical industrial design with modern methods of computer-program development and engineering modeling.

In the present article, the author seeks to correlate the fundamental conclusions and definitions presented in *Oleksandr Gudolin's* publications with the specific methodology and decision-making framework employed in contemporary computer-aided engineering systems incorporating elements of artificial intelligence.

As the challenges associated with the development, modernization, and optimization of technology and engineering systems continue to increase in complexity, isolated local solutions no longer satisfy the requirements of customers and developers seeking to achieve an ideal final result. Practical reality increasingly compels organizations to pursue composite, integrative, and comprehensive solutions, in accordance with the terminology and classifications optimized by *Oleksandr Gudolin* in his contemporary publications.

The identification and classification of all categories and levels of technical solutions directly affect the possibilities for systematic protection of existing and newly created intellectual property. This applies both to effective and active subsystems and to technical supersystems functioning as accumulators and integrators of the properties and characteristics of their constituent subsystems.

Modern technological innovations are frequently generated through intensive collaborative brainstorming processes involving multidisciplinary teams of specialists whose collective objective is the achievement of an optimal or ideal final result. Under such conditions, significant challenges arise in organizing and managing the innovation process. These challenges are often caused by objective factors, including psychological, technological, and engineering stereotypes that influence the perception and evaluation of new ideas.

Both existing and newly emerging technical and technological solutions are commonly assessed through the prism of historical experience derived from the application of the laws governing the development of industrial technologies, machines, and mechanisms. Many of these principles were formulated during the previous century, when contemporary materials, advanced components, modern industrial electronics, digital technologies, and laser-based systems were either unknown or unavailable and, consequently, could not be incorporated into engineering practice.

Figure 2. *Clearly demonstrates the capabilities of computer-based scaling technologies, which make it possible to obtain various sizes and configurations of technical systems within a single design process*



As a result, modern digital technologies incorporating artificial intelligence create opportunities not only for the development of fundamentally new technical systems but also for the reassessment and refinement of traditional engineering concepts, thereby enabling the emergence of innovative technical solutions that were previously impossible to conceive, model, or implement.

This situation is further complicated by the fact that, in the United States and in most other countries, the recognition of a technical solution as an invention is based on a number of specific criteria – four criteria in the United States and three criteria in many other jurisdictions.

The fourth criterion used in the United States introduces a subjective element into the evaluation of technical solutions. It is this factor that contributes to the gradual development and consolidation of a psychological stereotype based on the classification of new technical solutions as either obvious or non-obvious.

The presence of a clearly expressed subjective factor inevitably introduces comparisons between the proposed technical solution and previously known design elements, technological approaches, and combinations thereof derived from earlier developments.

The familiarity of a particular solution and the details of its implementation cannot be considered an objective evaluation criterion, since decisions regarding the obviousness or non-obviousness of a technical solution fundamentally depend upon the knowledge, experience, and professional competence of the patent examiners responsible for its assessment.

In modern engineering designs and technological solutions, novelty is no longer merely the reflection of a single technical discipline. Rather, it is the result of the integration of multiple disciplines, including electronics, microelectronics, advanced materials science, fiber-optic technologies, laser engineering, computer modeling, and digital control systems. Consequently, the assessment of obviousness or non-obviousness requires analysis from numerous disciplinary perspectives, which can only be adequately performed through collaboration between highly specialized experts and specialists

in multidisciplinary systems integration. As a rule, modern engineering design software, particularly software belonging to the SolidWorks family, enables the application of brainstorming techniques and the combination of various software capabilities for specialized design operations. These functions make it possible to address highly specific engineering requirements and performance characteristics associated with particular technical systems or groups of systems that ultimately form a comprehensive technical supersystem.

Naturally, much depends on the qualifications, experience, creativity, and analytical capabilities of the designer or software operator, as well as on their ability to interpret both conventional and unconventional technical parameters and performance indicators associated with a technical system functioning as a supersystem and incorporating numerous local technical systems operating as subsystems. At the same time, successful design and development activities require the ability to consider factors of unification and standardization while effectively combining them with original design solutions and innovative engineering features. The balanced integration of standardized components and novel design elements remains one of the key factors determining the efficiency, originality, and practical value of modern technical systems developed through advanced digital design technologies.

As illustrated in the figure, the current capabilities of the SolidWorks family of engineering design software make it possible to present a development not only as a complete assembly unit but also as a detailed set of individual components required for its assembly, including the visualization of each component and the complete assembly while taking into account the selected construction materials and their physical characteristics.

These capabilities, particularly when a development is intended to serve as a foundational technical solution for a future invention, require close coordination with the principles and methodologies of the Theory of Inventive Problem Solving (TRIZ).

TRIZ was originally conceived during the post-war period as a form of “exact science,” despite the fact that even at that time

an important debate existed within the inventive community regarding the fundamental importance of the individual inventor in achieving the declared Ideal Final Result (IFR), or its equivalent. The central question concerned whether the successful generation and selection of new technical solutions ulti-

mately depended upon individuals capable of producing useful and practically viable ideas. Today, it can reasonably be argued that the individual can play a significant role only when equipped with appropriate intellectual tools, foremost among them advanced software systems.

Figure 3. *Presents an example of a modern engineering design solution for a real-time liquid-homogenization system operating within a pipeline without the use of chemical reagents or stabilizing additives*



At that time, it was widely believed that any qualified specialist or professionally trained engineer, provided with a coherent and effective methodology for solving inventive problems, would be capable of generating new ideas and transforming those ideas into practical results. Consequently, the newly established Theory of Inventive Problem Solving, developed on both scientific-technical and psychological foundations, was received with considerable interest by the professional community.

For a certain period, the laws, principles, and methods of TRIZ generally corresponded to the prevailing level of technological development and industrial capability. The first significant inconsistencies became apparent with the introduction of automated production lines, followed by numerically controlled machine tools, and later by the emergence of digital technologies combined with advanced materials science, composite materials, in-

dustrial electronics, and computer-aided engineering systems.

Returning to the optimized definitions and classification terminology relating to technical solutions and the technical systems containing them, developed by *Oleksandr Gudolin*, it should be noted that, even independently of their significance for TRIZ theory, the clear and unambiguous definitions proposed by him have substantially improved the preparation of such important engineering documents as Technical Specifications, Technical Requirements, and, on the basis of these documents, Technical Design Assignments for new and innovative developments, while maintaining the highest possible level of compliance with applicable standards at all levels.

It is equally important to consider the degree and levels of standardization and unification of components and subsystems within the hierarchy of technical systems. Such systems may function as subsystems

relative to a higher-level technical supersystem while occupying the same hierarchical level as other subsystems. Consideration must also be given to the degree and level of integration of technical systems of equivalent hierarchical status into one another, since these relationships increasingly influence the design, development, optimization, and protection of modern complex engineering solutions.

In the context of contemporary digital design technologies incorporating elements of artificial intelligence, these classification principles acquire particular importance. They facilitate a more accurate understanding of the structure, evolution, and innovative potential of technical systems while improving the effectiveness of engineering decision-making, intellectual property protection, and the management of complex multidisciplinary development projects.

Figure 4. *Presents the same project shown in Figure 1, but supplemented with sectional views that provide a complete representation of the internal structure of the technical solution and the geometric requirements applicable to its individual components*



These capabilities do not exhaust the full functionality of modern computer-aided design systems; however, the application of TRIZ principles, definitions, and methods in combination with such software technologies can further increase the efficiency of innovative developments while simultaneously reducing both design costs and development time.

This raises an important question: what does TRIZ actually represent under contemporary technological conditions? How have modern high technologies, digital engineering tools, and advanced processor systems influenced its compositional and integrative capabilities?

These are only some of the issues requiring clarification. Equally important is the widespread tendency toward the detailed investigation of biological systems and biological or medical objects in search of effective analogues for future inventions, particularly within the field of biologically inspired mechanical engineering.

A significant question therefore arises regarding the relationship between such approaches and the laws, methods, and techniques of TRIZ and ARIZ (Algorithm of Inventive Problem Solving).

Today, the majority of highly effective and innovative inventions emerge from discoveries and systematic analyses of phenomena

observed in nature. Biological systems increasingly inspire inventors to create complex integrative technical solutions capable of addressing unconventional problems through unconventional methods, many of which are derived from the principles governing the evolution and functioning of living systems. Owing to the capabilities of modern digital technologies, such concepts can be modeled, simulated, and evaluated systematically before the preparation of initial technical requirements and technical specifications for inventors and design teams.

Numerous examples of such developments can already be identified. More importantly, the process of creating new methods and styles of computer-aided design continues to evolve and expand in parallel with the constantly increasing capabilities of computer hardware, software platforms, artificial intelligence systems, and digital engineering environments.

For inventors and developers, one of the most important and challenging tasks has been the accurate determination of numerous parameters and relationships within technical systems, particularly in cases where no previous developments or engineering precedents existed.

The application of methods recommended by TRIZ, despite the absence of similar integrations in earlier developments, made it possible to create a fundamentally new product that approached the threshold of the Ideal Final Result.

This achievement immediately resolved a number of technical, innovative, and integration-related challenges and made it possible to obtain complete autonomy for the system under development.

Furthermore, the autonomous operating period of the system proved to be virtually unlimited.

Thus, overcoming a multidisciplinary engineering problem complex, combined with the elimination of a significant psychological barrier, enabled developers to address the remaining design challenges through the application of integrated, modified, and optimized TRIZ methodologies and techniques.

The integration methodology described above, applied during the synthesis of innovative technical solutions, has become the focus of numerous organizational, technological, engineering, and scientific initiatives.

In this context, it is noteworthy that on September 8, 2011, the United States Senate approved patent-reform legislation known as the America Invents Act. As the U.S. economy has increasingly evolved into an innovation-driven economy, its innovative nature has generated substantial new requirements for patent legislation. Moreover, the emergence of artificial intelligence elements within software systems and process-control platforms has created – and continues to create – a clear necessity for the systematic revision and adaptation of the fundamental laws governing the development of technical systems at all hierarchical levels.

Figure 5. *Illustrates the design of one of the fundamental components of the technical system presented in Figures 3 and 4. Unlike the previous design, this component is manufactured from a metal-ceramic material with a high carbon-carbon composite content instead of stainless steel*



Under these conditions, modern digital technologies incorporating artificial intelligence are not merely design tools; they are becoming active participants in the innovation process, influencing the generation, evaluation, optimization, integration, and implementation of new technical solutions and thereby reshaping the methodology of industrial design itself.

The figure demonstrates the advanced capabilities of comprehensive digital design simulation for all elements of the assembly. Where the external appearance and surface finish are critical to the subsequent operation of the technical system, such visualization provides maximum design information and enables a detailed representation of the assembly as a subsystem within a higher-level technical supersystem.

The author presents a representative example from contemporary engineering design practice. Catalogs and websites of leading manufacturers of standard components and assemblies now provide not only engineering drawings but also three-dimensional CAD models, for example, in SOLIDWORKS format. Designers can directly incorporate these models into their own technical solutions developed within the same CAD environment.

This approach fundamentally transforms the engineering design process by enabling the selection, evaluation, and integration of alternative components in real time while simultaneously incorporating supplier-provided engineering data as an integral part of the developing technical solution and its subsequent integration into all hierarchical levels of the technical system.

The author further discusses recent developments in patent legislation based on the “first-to-file” principle, under which patent rights are granted to the first applicant to file a patent application. This approach has significantly simplified the resolution of patent priority disputes by eliminating the need to establish inventorship during the examination process, although evidence of priority may still be introduced in judicial proceedings to challenge the validity of an issued patent.

This principle also has important organizational, investment, and psychological implications, influencing the working environment of technology development teams, the rela-

tionships between competing companies and investment organizations, as well as the role of component suppliers, which have become full participants in the engineering design process.

Today, the first-to-file system is applied in virtually all developed countries, including the United States.

However, apart from so-called hybrid inventions in the field of software, the fundamental issues remain unchanged. The recognition of software as patentable subject matter – despite the fact that software itself cannot be equated with a technical solution – has resulted in the issuance of numerous patents for applications that contain little or no genuine technical innovation.

The relative ease with which thousands of software-based and partially software-based patents have been granted has blurred the traditional criteria of technical operability and inventive novelty. As a consequence, and partly due to the resulting uncertainty experienced by investors, a parallel process has emerged in which patent litigation, rather than technological innovation, becomes the primary driving force. In this environment, the central figure is increasingly the patent attorney rather than the inventor, with the emphasis shifting from innovation to legal disputes.

Consequently, the challenges arising from contradictions and limitations within the **TRIZ** methodology are insignificant compared with the broader problems created – and to some extent stimulated – by the ambiguity and imperfections of modern patent legislation.

According to the author, the application of **TRIZ**, advanced analytical methods, computer modeling, and techno-dialectical synthesis to comprehensive technological forecasting may provide new opportunities for improving innovation processes, particularly in the fields of biotechnology and genetic engineering.

One of the undeniable strengths of **TRIZ** since its inception has been its attempt to apply dialectical principles to inventive problem solving through the identification and resolution of technical contradictions.

To achieve this objective, **TRIZ** introduced a specialized algorithm (**ARIZ**), consisting of a sequence of logical procedures designed to formulate an inventive problem

as a system of contradictions and to provide recommendations for their resolution.

In addition, the TRIZ literature contains numerous illustrative examples and practical problems that possess significant educational and methodological value.

However, considering the current state of engineering design, an important question arises: **what if a contradiction, in its classical interpretation, does not actually exist?** In such cases, how can one resolve contradictions that are not present?

Partial answers to this question are provided by the latest capabilities of modern computer-aided engineering and design software.

The depth and level of detail achievable during even the preliminary design stage make it possible to perform a complete cycle of computer modeling and simulation of the device's operating process using initial conceptual models, without the need to manufacture physical prototypes for experimental testing.

Furthermore, eliminating the need for a dedicated budget to validate conceptual designs significantly reduces development time while allowing substantially greater resources and effort to be devoted to the synthesis, optimization, and further development of innovative technical solutions.

These capabilities also fundamentally transform the psychological and professional relationships between technology developers, equipment designers, and investors. The traditional concern over costly design errors is greatly reduced because comprehensive computer modeling and simulation enable potential deficiencies to be identified, analyzed, and corrected at an early stage while simultaneously suggesting more efficient alternative directions for the further development and optimization of the project.

Let us consider the following laws governing the evolution of technical systems:

1. The Law of Completeness of the Parts of a Technical System.
2. The Law of Increasing the Degree of Ideality of a Technical System.
3. The Law of Human Elimination from a Technical System.

4. The Law of Coordination of the Rhythms of System Components.
5. The Law of Energy Conductivity of a Technical System.
6. The Law of Uneven Development of the Parts of a Technical System.
7. The Law of Transition from the Macro-Level to the Micro-Level.
8. The Law of Increasing the Degree of Substance-Field Interactions.

Let us also adopt the modified classification of technical systems proposed by *Oleksandr Gudolin* in his publications:

- Technical System
- Local Technical System
- Advanced Technical System
- Global Technical System
- Intelligent Technical System

The **Ideal Final Result (IFR)** is defined as achieving the desired outcome or solving a problem without increasing the complexity of the technical system while minimizing the consumption of resources, including financial costs, development time, materials, clean water, and other essential resources. From the perspective of environmental protection, the concept of the IFR encompasses all resource-efficient, waste-free, and environmentally sustainable technologies.

The formulation of the Ideal Final Result begins with identifying the primary useful function of the technical system – that is, answering the fundamental question: **“Why was this system created?”** For example, the primary purpose of a mobile telephone is to enable communication in the absence of a fixed-line telephone. Accordingly, the Ideal Final Result is the ability to establish instantaneous communication with any person anywhere in the world, a capability that has been substantially advanced through modern Internet technologies.

Under contemporary engineering conditions, the formulation of the IFR serves several essential objectives.

First, it establishes the design objective and determines the direction of technological development. Today, the validity of selecting this objective can be verified through advanced computer simulation and digital modeling, allowing engineers to predict system output parameters and evaluate their variations in response to changes in

the characteristics of standard components incorporated into subsystem architectures. These component models are increasingly supplied directly by manufacturers as validated digital engineering models.

Second, it minimizes unnecessary trial-and-error during the search for engineering solutions. Modern computer models of technical systems enable designers to generate, evaluate, and simulate numerous design alternatives while varying the performance characteristics of all subsystem components throughout the hierarchy of the overall super-system. As a result, the number of experimental iterations required during conceptual development is reduced to a practical minimum.

Third, it ensures a high level of quality for the final engineering solution. Here again, priority is given to computer-based simulation of production processes and operating cycles, enabling comparative evaluation of system performance, reliability, efficiency, and other qualitative indicators before physical prototypes are manufactured.

The concept of the IFR is closely associated with that of the **ideal technical system** – a system that does not physically exist while its intended function is nevertheless fully performed. Although such an ideal state cannot always be achieved in practice, it serves as the ultimate direction of technological development.

Accordingly, engineering efforts are directed toward increasing the **ideality** of technical systems, defined as the ratio between the useful functions performed by a system and the total resources required for its design, engineering, manufacturing, operation, and maintenance.

Naturally, the formulation of the Ideal Final Result must remain fully consistent with applicable technical standards, regulatory requirements, industry specifications, and engineering codes. While these constraints inevitably limit the degree of design freedom, they simultaneously ensure the practical feasibility, safety, and regulatory compliance of innovative engineering solutions.

The foregoing considerations provide the basis for re-examining the fundamental laws governing the evolution of technical systems from the perspective of today's capabilities in computer-aided engineering, digital design,

advanced manufacturing technologies, and modern operational methodologies.

The Law of Completeness of a Technical System

A fundamental prerequisite for the viability of any technical system is the presence and minimum operational capability of all its essential components. Since the operational performance of these components can now be reliably verified through computer modeling during the design stage, their minimum functional capability can be accurately assessed during system development. Consequently, in modern engineering practice, compliance with this law is largely ensured before the product reaches the market and rarely presents challenges beyond routine maintenance during subsequent operation.

The Law of Energy Conductivity of a Technical System

A fundamental condition for the viability of a technical system is the uninterrupted transfer of energy throughout all of its components. Compliance with this law can likewise be accurately verified through computer modeling by selecting only those components whose performance fully satisfies the required energy transfer characteristics. For modern computerized technical systems, the law of energy conductivity constitutes one of the fundamental principles governing reliable and efficient system operation.

The Law of Coordination of the Rhythms of System Components

A necessary condition for the viability of a technical system is the coordination of the operating rhythms, frequencies, and periodic behavior of all system components. In contemporary engineering, compliance with this law is achieved through computer simulation and digital coordination of the operating characteristics of every subsystem, including components controlled by programmable processors and industrial controllers.

The Law of Increasing the Degree of Ideality

The evolution of technical systems proceeds toward increasing their degree of ideality. Comprehensive computer modeling

and simulation of all system components under both static and dynamic operating conditions make it possible to optimize not only the performance of individual subsystem combinations but also the overall ideality of the complete supersystem within integrated engineering projects.

The Law of Uneven Development of System Components

The components of a technical system evolve at different rates. The more complex the system, the greater the disparity in the development of its individual parts. However, under today's conditions of global technological integration, it has become possible to select both primary and auxiliary components that represent comparable levels of technological maturity, thereby minimizing developmental imbalance among subsystems within the supersystem and throughout the subsequent hierarchical levels in which the supersystem itself functions as a subsystem.

The Law of Transition to a Supersystem

After exhausting its own developmental potential, a technical system becomes integrated into a supersystem as one of its constituent elements, with further development occurring at the supersystem level. In modern engineering, where flexible computer control systems and Internet-based data exchange are widely implemented, the transition of a subsystem into a supersystem is increasingly determined by the computational capability, processing speed, and functionality of embedded computer systems.

The Law of Transition from the Macro-Level to the Micro-Level

The evolution of a system's working elements proceeds initially at the macro level and subsequently at the micro level. With processors, programmable controllers, supervisory computers, and Internet-connected

monitoring systems participating throughout the design, manufacturing, and operational stages of a technical system, the traditional distinction between macro- and micro-level processes becomes increasingly indistinct. Under such conditions, a system functioning as a subsystem may effectively operate as a supersystem when connected, for example, to cloud-based information storage and distributed control environments.

The Law of Increasing the Degree of Substance-Field Interactions

Technical systems evolve toward increasing the number and complexity of substance-field interactions. The widespread incorporation of computerized monitoring and control systems creates numerous additional substance-field relationships, including direct and feedback communication channels, as well as information, control, and monitoring signals exchanged throughout every hierarchical level of the technical system. This significantly increases the degree of substance-field interaction while simultaneously expanding the number of functions that can be monitored, controlled, and optimized.

Conclusion

In future publications, it will be appropriate to return to specific examples of contemporary engineering developments in light of the above observations concerning the laws governing the evolution of technical systems, while also considering the modified definitions and classification of technical systems of varying structural and technological complexity proposed by *Oleksandr Gudolin* in his published works. These updated interpretations provide a more comprehensive framework for analyzing modern engineering systems operating within highly integrated digital design, manufacturing, and control environments.

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submitted 18.05.2026;
accepted for publication 02.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-241-247



**SAFETY OF ENERGY-GENERATING EQUIPMENT THROUGH
INNOVATIVE CYBERSECURITY APPROACHES. (Issues of
ensuring the reliability, stability, and operational safety of
energy-generating equipment, including through the
application of innovative cybersecurity technologies
and advanced cyber-protection solutions)**

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Cite: Ogannisyan V. (2026). *Safety of energy-generating equipment through innovative cybersecurity approaches. (Issues of ensuring the reliability, stability, and operational safety of energy-generating equipment, including through the application of innovative cybersecurity technologies and advanced cyber-protection solutions). Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-241-247>

Abstract

The article examines issues related to ensuring the stable, reliable, and secure operation of energy-generating equipment through the application of innovative cybersecurity technologies and advanced fuel-management solutions. Particular attention is devoted to the role of embedded processors and controllers in supporting autonomous operation, online monitoring, operational control, and computer modeling of equipment operating parameters without requiring significant external computing resources.

The publication analyzes contemporary approaches to adapting energy-generating systems to alternative fuel technologies, including the increasing use of methanol-based fuel mixtures. Special emphasis is placed on engineering solutions developed for gas turbines operating with methanol concentrations ranging from partial substitution to the complete replacement of conventional diesel fuel.

The study considers the technological challenges associated with changes in fuel composition, including the need for the rapid reconfiguration of monitoring and control systems, software updates, and recalibration of operational parameters. The author examines innovative methods for the dynamic mixing of methanol with conventional diesel fuel to improve combustion characteristics, increase operational efficiency, and compensate for the specific thermodynamic properties of methanol.

Particular attention is given to the development of simple, reliable, and mobile cybersecurity solutions designed to protect control and information systems without requiring substantial modifications to existing equipment designs, operational schemes, or engineering configurations. The article highlights the importance of information-security systems capable of protecting operational software and data-storage media while maintaining compatibility with existing energy infrastructure.

The conclusion emphasizes the prospects for integrating advanced cybersecurity technologies, intelligent monitoring systems, and innovative fuel-management solutions into modern energy-generating equipment in order to improve operational safety, increase fuel efficiency, enhance environmental performance, and support the long-term modernization of energy-production systems.

Keywords: *Energy-generating equipment; Cybersecurity; Innovative aspects of cybersecurity; Computer modeling of operating-cycle parameters of energy-generating equipment; Engineering resources; Embedded processors and controllers; Increasing proportion of methanol in fuel mixtures; Designs and circuit configurations of energy-generating equipment; Modification and optimization approaches for turbine fuel systems; Complete substitution of diesel fuel with methanol; Innovative methods of dynamic mixing of methanol with small proportions of conventional diesel fuel; Intelligent monitoring and control systems; Fuel-efficiency optimization; Digital technologies in energy production; Reliability and operational safety of power-generation systems; Advanced fuel-management technologies*

Introduction

Energy-generating equipment is inherently highly autonomous during operation, and issues related to operational management and online monitoring can, in many cases, be effectively addressed using the processing capabilities of the equipment's embedded processors and controllers.

In numerous applications, computer modeling of operating-cycle parameters can also be performed using these internal computational resources, provided that the modeling tasks are properly formulated and optimized from both technical and economic perspectives.

The Israel Electric Corporation possesses substantial engineering resources dedicated to optimizing electricity-generation processes, including the application of advanced fuel mixtures consisting of diesel fuel and methanol, with an increasing trend toward methanol concentrations reaching 95–100% of the fuel composition.

Changes in fuel type and composition require the rapid reconfiguration of all monitoring and control systems, as well as the deployment of specialized software capable of accounting for all modifications in equipment operating parameters, control-system settings, and calibration procedures.

Industrial operating conditions require protection methods and devices that can provide comprehensive and reliable protection for monitoring and control equipment without complicating existing operating procedures. Such solutions should preserve virtually all circuit, kinematic, and fundamental design elements of the original equipment

while introducing new protective components that do not require modifications to the base equipment during implementation.

Industrial experience and operational practice have demonstrated the need for mobile and highly simplified protection systems capable of supporting autonomous equipment operation without introducing additional information-storage media into existing operational architectures.

During the evaluation and analysis of available protection technologies, specialists of the Israel Electric Corporation concluded that the most economical and effective approach would be a data-storage protection system that does not require substantial modifications to the design or circuit architecture of energy-generating equipment.

The Israel Electric Corporation is recognized as a pioneer in the application of methanol as an alternative fuel for power-generating gas turbines.

Gas turbines of this capacity range (20–25 MW) traditionally utilize Diesel Fuel No. 2 as their primary fuel source.

One of the original objectives established by the development team responsible for the new innovative technology was the utilization of the so-called evaporation energy of methanol, which is significantly higher than that of other commonly used liquid fuels.

To achieve this and other innovative objectives, various modifications and optimizations of the turbine fuel system were developed. In addition to configurations providing complete replacement of diesel fuel with methanol, these solutions included innovative systems for the dynamic mixing of meth-

anol with small proportions of conventional diesel fuel.

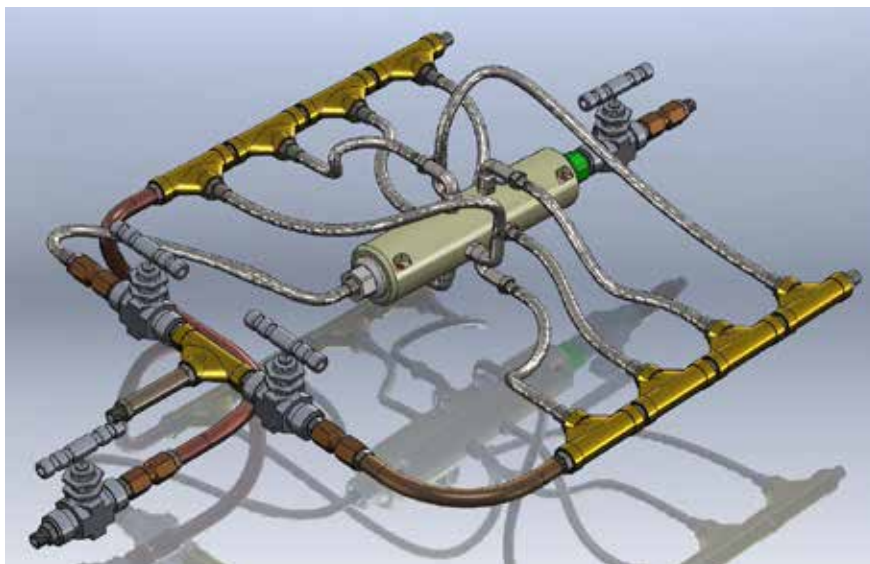
Such mixing strategies made it possible to reduce the influence of certain methanol properties on the combustion process, particularly those associated with methanol's relatively low flame temperature.

Given that hundreds and thousands of long-service-life turbines currently remain in operation worldwide and utilize a variety of fuels—including heavy diesel fuels such as fuel oil, natural gas, coal dust, and other fuel blends—it is appropriate to examine the differences between adaptation systems designed for the dynamic mixing of methanol with these fuel types, as well as the characteristics of the mixing devices themselves.

During prototype verification and qualification testing, the fundamental technical solutions associated with such devices were evaluated. These solutions demonstrated certain design differences depending on the type of fuel utilized and the number of fuel components involved in the mixing process.

At the same time, despite the high degree of unification and standardization achieved in modern fuel-preparation and fuel-mixture systems, the overall infrastructure of thermodynamic equipment remains highly dependent on the mobility, efficiency, and reliability of control, monitoring, and calibration systems, including the real-time adaptation of all incoming and outgoing operational signals.

Figure 1.



The first figure presents a three-dimensional model of a device designed for the dynamic mixing of diesel fuel and methanol directly within the fuel line of thermodynamic equipment.

The device is extremely simple in design and, even in this configuration, may be used in at least two different ways: as a static mixer, since it contains no moving parts, and as a static online fuel-homogenization device operating directly within the fuel-supply line.

Due to the unique characteristics and complexity of energy-generating equipment, the integration of even such a compact and simple device into the fuel system requires appropriate adjustments to the operating parameters of the equipment. This, in turn,

necessitates modifications to the software controlling the embedded processors and on-board computer systems.

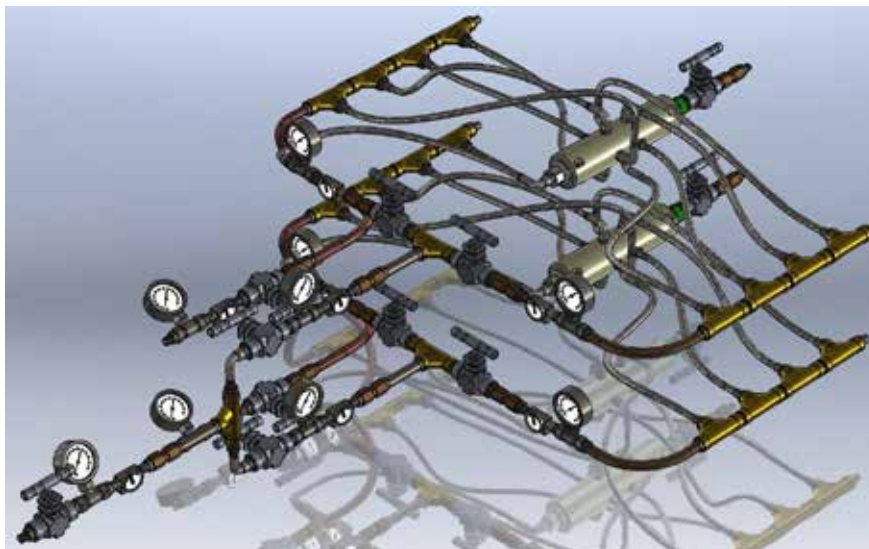
From the perspective of mechanical and hydraulic installation, the process of implementing such modifications is entirely conventional and does not present significant technical difficulties. However, from the standpoint of cybersecurity, the temporary interval required for software modification, updating, or replacement creates a potential vulnerability window through which malicious software or computer viruses may gain access to the control and monitoring systems of thermodynamic equipment.

Considering the inherent inertia of such systems, it may be assumed that the detection

of unauthorized intrusion could occur only after a certain period of operation. During this time, malicious software could potentially affect or

disable critical components and subsystems of the equipment before the intrusion is identified and corrective measures are implemented.

Figure 2.



Furthermore, if a dual mixing system is integrated into the equipment, the corresponding cybersecurity risk is effectively doubled. In addition, where the system incorporates a recirculation loop for excess fuel, a significantly larger number of components and mechanisms may become exposed to the influence of malicious software, thereby further increasing the risks associated with modernization and system adaptation.

Under real operating conditions, there is often a need for substantially higher volumetric or mass fuel-flow rates. For example, when comparing the calorific value of methanol with that of conventional diesel fuel, methanol possesses approximately half the energy content of diesel fuel. Consequently, modernization for methanol operation requires an increase in fuel consumption by more than two times in order to maintain equivalent energy output.

This requirement further complicates the modernization process and necessitates the installation of approximately twice as many fuel-handling devices, together with all associated monitoring, control, and management elements.

Such a configuration imposes additional demands on the processing power, memory capacity, and operational capabilities of em-

bedded processors and programmable controllers, thereby further confirming the validity of the conclusions outlined above.

The following figure illustrates such a quadruple-system configuration comprising four independent units, each of which may, if necessary, operate autonomously within the overall fuel-management and control architecture.

In recent years, powerful and highly productive systems have emerged that are capable, in principle, of replacing multi-component configurations while maintaining equivalent or even superior thermodynamic performance characteristics.

The following figure illustrates such a system with a processing capacity of 1,000 liters per hour.

Although this system incorporates only three external inlets and a single outlet, the specific requirements associated with its control, monitoring, and hydrodynamic coordination demand no fewer control and management operations than more complex multi-component systems. Consequently, it requires comparable computational capabilities from the associated control, monitoring, and operating-cycle simulation systems used in thermodynamic equipment.

Accordingly, the importance of ensuring high-quality and guaranteed protection of software components during the operational

loading of control, monitoring, and analytical systems remains critically important re-

gardless of the type or configuration of the fuel-mixing device employed.

Figure 3.



When considering the fundamental technical requirements applicable to such systems, the following key criteria may be identified:

- Information-storage media must possess original integrated security features;
- Software loading and updating procedures must be protected against unauthorized access and malicious interference;
- Control and monitoring systems must ensure the integrity, authenticity, and traceability of operational software throughout the entire service life of the equipment;
- Protection mechanisms should function without requiring substantial modifications to the existing design, architecture, or operational principles of the equipment;
- Security systems should support autonomous operation and maintain functionality under industrial operating conditions;
- Cybersecurity measures should ensure reliable protection against unauthorized software modification, malicious code injection, and external cyber threats targeting critical control and monitoring infrastructure.

Figure 4.



- Information-storage media must possess an identification system and methodology equivalent to those used in processor-based and onboard computer systems for data recognition and verification;
 - The identification code must be applied to the information-storage medium in such a manner that the standard dimensions, geometry, and configuration of the medium's interface and connection elements remain unchanged;
 - The identification code should be based on a single control and measurement parameter;
 - Identification of this parameter must be performed using a non-contact method.
- The above requirements represent only a portion of the key technical criteria. However, under current technological conditions, no commonly used mobile information-storage medium fully satisfies these requirements, even partially.
- In this regard, it should be noted that, after reviewing the highly significant publications of *Babadzhanian Heorhii*, an Associate Member of the Ukrainian Academy of Sciences, dedicated to this field, our working group concluded that it was extremely important to evaluate and test the information-storage media coding system proposed in his publications.

Figure 5.



As demonstrated in these publications, the developments proposed by *Babadzhanian Heorhii* collectively satisfy all of the

above-mentioned technical requirements, as well as a considerable number of additional independent requirements and their combi-

nations. Furthermore, these developments establish the foundation for a new and promising technological field based on magnetic-resonance, non-contact methods of control and nano-scale measurement.

From the perspective of a specialist involved in the operation of industrial power-generation equipment, the most effective application of this method appears to be its dissemination among manufacturers and operators of specialized computer systems used in power-generation facilities.

Given the clear scalability characteristics of fuel-mixing and fuel-preparation equipment, it may be reasonably assumed that the proposed coding system can be implemented throughout virtually all sectors of the energy industry, including gas turbines, diesel generators, boiler systems, combined heat and power plants, and other types of thermodynamic equipment.

The following figure presents three-dimensional models of dynamic fuel-mixing devices arranged according to size and scale factors. The smallest systems may be inte-

grated into compact industrial or domestic equipment, whereas the largest systems are capable of supporting fuel-flow rates reaching tens of thousands of liters per hour.

The proposal developed by *Babadzhanian Heorhii* significantly expands the potential integration opportunities for innovative energy projects. Even within a single power-generation facility with a capacity of several tens of megawatts, such an approach may generate annual savings measured in hundreds of thousands of dollars while simultaneously providing the highest achievable level of protection for energy-equipment control architectures and management systems.

Moreover, within the context of modern energy technologies, this proposal demonstrates originality of concept, innovative thinking, and the exceptional nature of a new technological and software-oriented direction. With relatively modest implementation costs, it offers a practical solution to one of the most critical challenges facing contemporary energy systems—the achievement of an adequate and reliable level of cybersecurity.

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submitted 15.06.2026;

accepted for publication 29.06.2026;

published 30.06.2026

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DOI:10.29013/AJT-26-5.6-248-255



WATER PURIFICATION IN INNOVATIVE ECOSYSTEMS. (Integrative inventions for the purification of process water with the aim of its recirculation)

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Cite: Skokova L. (2026). Water purification in innovative ecosystems.(Integrative inventions for the purification of process water with the aim of its recirculation). Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6. <https://doi.org/10.29013/AJT-26-5.6-248-255>

Abstract

The article examines the development and implementation of integrative technological solutions for the treatment, purification, and regeneration of contaminated process water with the aim of its recirculation. It describes a scalable, modular, and adaptive system based on synchronized electrochemical and hydrodynamic processes that enable effective removal of organic and inorganic impurities, including metals, sulfates, phosphates, oils, and other contaminants. Particular attention is given to the design of an electrochemical reactor with parallel electrode cells and a synchronized power supply system, ensuring stable operation under fluctuating conditions. The study highlights the role of coagulation, sedimentation, and redox reactions in forming removable impurity complexes, as well as the importance of automated control systems with feedback for process stabilization. The proposed solution is characterized by low energy consumption, high efficiency, and adaptability to varying conditions, including low-conductivity water. Its modular design enables integration into larger systems and supports autonomous operation.

The article also outlines structural and technological features that enhance performance, such as synchronized current supply and optimized flow conditions, demonstrating improved treatment efficiency and environmentally sustainable water treatment for industrial and wastewater applications.

Keywords: Water; Organic impurities; Inorganic impurities; Impurity complexes; Automated water treatment module; Environmentally friendly production; Automatic process control and feedback; Computerized module; Coagulation; Sedimentation; Electrodes; Power supply units; Energy delivery mechanism; Power supply units; Synchronously connected power supply units

Introduction:

In recent years, with the emergence of so-called smart technologies across many indus-

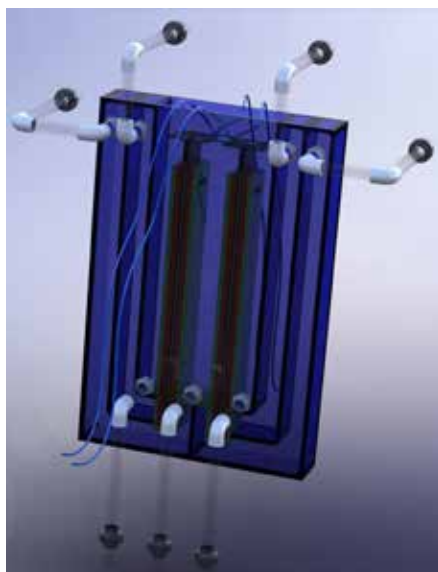
tries, along with their corresponding smart components, conditions have arisen in various application areas for the development of

integrative patents. These patents combine features and distinctions of devices (apparatuses), complex systems (supersystems and their constituent subsystems), software, and associated methods.

This direction has developed particularly intensively with the incorporation of artificial intelligence elements and artificial neural networks into control and monitoring systems.

In turn, the advancement of core technologies as part of the ecosystem and infrastructure of smart manufacturing environments requires the systematic development of production and infrastructure modules – primarily comprehensive process water treatment systems that operate without chemical reagents and are based on electrochemical reactors performing treatment in an upward flow of the processed liquid.

Figure 1. *Electrochemical reactor with two electrochemical cells*



Brief product description

Proprietary integrated, scalable, adaptive, and modular systems and equipment, as well as technical support services for the treatment/purification/regeneration of commercial types and volumes of contaminated flowing water.

They are based on the separation and removal of inorganic and/or organic impurities (such as metals, sulfates, phosphates, oils, and lubricants) from contaminated water flowing through and interacting with electrodes placed in at least two electrode cells, specifically de-

signed and constructed to ensure a stable and synchronized electrochemical process and hydrodynamic flow conditions.

An efficient and cost-effective design and operation of the energy supply mechanism, including a pair of synchronously connected and operating power supply units, provide synchronized power delivery to the electrodes, which oxidize and reduce components in the contacting flowing water.

The formed oxidized/reduced components of the water create complex impurities in the flowing water through mechanisms including coagulation and sedimentation, thereby forming impurity complexes that are removed, for example, by sedimentation, from the flowing water.

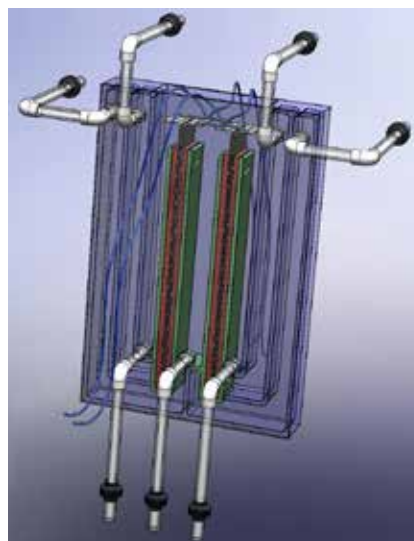
The system is automated and computerized, including equipment, procedures, and software for automatic process control and feedback.

Part 1 – General introduction and overview

The following provides a general introduction and overview of the water treatment/purification/regeneration system.

The invention relates to the general field of water treatment/purification/regeneration, and more specifically to a method, device, and system for the treatment/purification/regeneration of commercial types and volumes of contaminated flowing water.

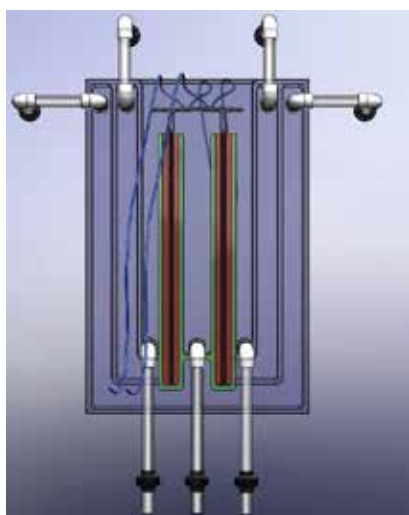
Figure 2. *Internal structure of the electrochemical reactor housing with two parallel electrochemical cells*



The invention is characterized by a set of synchronized and synergistically interconnected electrochemical and hydrodynamic properties, characteristics, behaviors, and phenomena that are novel (unanticipated) and inventive (not obvious from) prior art in the field of water treatment/purification/regeneration.

The structure and operation of the invention and its components are designed, constructed, and implemented using conventional engineering methods, equipment, and materials, based on well-established physical, chemical, and related mathematical theories, laws, and principles.

Figure 3. *Electrochemical reactor with upward-flow water treatment*



The invention corresponds to a new and unique synchronized and synergistic model of a nonlinear system influenced by continuously occurring fluctuations in key system parameters associated with the treated flowing water, namely the concentration of chemical components and the electrical conductivity of the water.

Since the invention for treating contaminated flowing water must operate under fluctuating conditions, it therefore includes provisions for mitigating “selective instabilities” characteristic of most environmental technologies. This is achieved through mechanisms of an “organic” or “natural” nature, which, as part of the described invention for water regeneration, enable synchronization and synergistic interconnection of electrochemical and hydrodynamic properties, characteristics, behaviors, and phenomena.

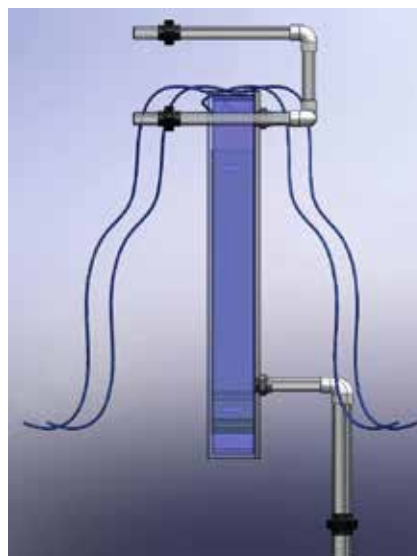
An important objective of the invention is based on comprehensive and well-founded principles of synchronization and synergy applicable to the technology of complex treatment of contaminated flowing water.

The invention addresses the task of creating an efficient, mobile, adaptive, and self-sufficient device (an electrochemical and hydrodynamically stable reactor) as part of a larger overall system for the regeneration of contaminated flowing water.

The effectiveness of the proposed technical solution is ensured by:

- low levels of energy consumption required for the process;
- low levels of non-productive energy losses within the process cycle;
- the possibility of combining and synchronizing certain energy-intensive autonomous technological tasks, such as electrolytic dissolution of the anode (electrolytically coagulating element) and the simultaneous formation of regions with highly concentrated oxidizing agents;
- reduction of process duration through precise synchronization of cycle timing with the interaction of technological stages;
- stabilization and synchronization of process rates, concentrations, energy consumption, and time factors;
- a high level of reproducibility and technical standardization of the process.

Figure 4. *Electrode proportions of the electrochemical reactor*



The mobility of the proposed solution is ensured by the following:

- a minimized design;
- a modular structure with full synchronization of modules;
- a flexible interaction scheme between modules, with the possibility of synchronized switching of additional treatment stages, allowing operation during transitional periods.

The proposed technical solution is adaptable due to:

- synchronous automatic adjustment of process power supply parameters in response to changes in operating conditions and initial characteristics, such as variations in water conductivity;
- a modular, autonomous system consisting of identical energy-converting and generating units operating synchronously to supply power to the process;
- a feedback sensor system providing signals used to stabilize and synchronize process parameters.

The autonomy of the proposed solution is ensured by:

- a complete cycle of technological operations and transitions synchronized across all parameters, providing the required final regulation;
- a fully autonomous system capable of treating various types and volumes of contaminated flowing water sources;
- synchronized integration of different treatment/purification/regeneration operations to achieve optimal results;
- extraction of conventional outcomes from the process, such as pH adjustment.

The main advantages of the invention for the treatment/purification/regeneration of contaminated flowing water are based on the implementation of fundamental characteristics of the invention and the following structural and technological achievements:

- effective stimulation of co-sedimentation (multi-sedimentation) in the presence of metals and other materials in contaminated water, enabling their precipitation under fundamentally different conditions;

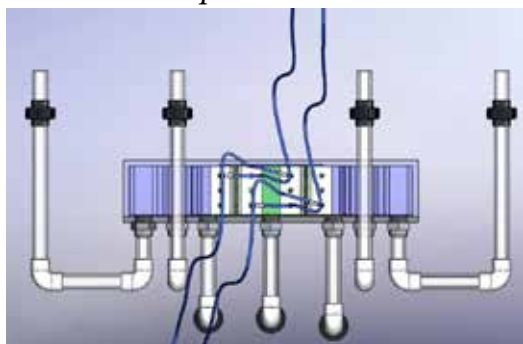
- effective stimulation of co-sedimentation without significant changes in water acidity or alkalinity;
- simultaneous implementation of hydroxidation and electrocoagulation without additional energy or time costs;
- efficient treatment of contaminated flowing water sources within short timeframes, enabling acceleration of automated production lines;
- acquisition of indirect data on changes in easily measurable system parameters during treatment, using feedback to assess the quality of treated/regenerated water;
- acceleration of automated control systems;
- enhanced performance of flexible automated technological modules and complexes;
- adaptability to treatment of very low-conductivity water (e.g., 1–5 μS);
- achievement of a twofold increase in electrical current or voltage parameters without additional energy consumption, by adjusting one parameter without changing the other;
- remote control of the system, including monitoring of process parameters and elimination of imbalances between electrochemical and hydrodynamic conditions;
- autonomous local shutdown and remote control without reprocessing already treated water, enabling closed-loop recirculation;
- rapid adjustment of operating modes, with automatic synchronization of DC power sources and the hydrodynamic system under varying configurations and interaction modes;
- integration of the invention into larger systems and processes, such as reverse osmosis and ultrafiltration systems.

Additional advantages provided by advanced characteristics of system components include:

- the presence of at least two synchronously operating DC power sources;
- series connection with voltage doubling relative to that required for a given conductivity, resulting in increased concentrations of oxidizing and reduc-

- ing agents and a higher proportion of hydroxides in the treated water;
- parallel connection with current doubling, leading to higher concentrations of oxidants and reductants and improved precipitation quality;
- enhanced coagulation in high-current mode (up to approximately A/dm^2), enabling dissolution of aluminum electrodes and achieving reaction rates approximately twice those of conventional electrocoagulation (typically $1-2 A/dm^2$);
- capability for electrolytic recovery of precious metals during hydrodynamic stabilization as water passes between electrodes;
- applicability for seawater treatment;
- real-time monitoring capability with automatic fault detection, recovery of synchronized operation, and notification of system status;
- maintenance of output water quality with reduced power consumption compared to a single high-power source;
- presence of common cathode and anode sections within interelectrode spaces;
- higher electric field intensity in interelectrode regions;
- reduced hydraulic resistance to water flow;
- increased concentration of generated oxidizing and reducing agents;
- prevention of salt shedding from the cathode;
- avoidance of anode scale accumulation;
- improved usability of system characteristics;
- extended electrode service life.

Figure 5. *Electrochemical reactor – plan view*



Part 2 – Structure, function, and operation

The following provides a detailed and illustrative description of the structure, function, and operation of the main and alternative embodiments, as well as their components, of the water treatment/purification/regeneration system.

Heterocoagulation:

The installation of electrode cells with aluminum or pure iron anodes in the electrochemical reactor for water treatment/purification/regeneration produces an effect in which the primary process of generating oxidizing and reducing agents in the water flow is supplemented by anodic by-products that act as coagulants. This facilitates the process associated with the required separation of substances in the dispersed phase from the dispersion medium.

This “coagulation threshold” increases relatively rapidly. In most cases, the flowing contaminated water contains various salts of multivalent metals, which hydrolyze to form colloidal hydroxides. This stimulates the process of heterocoagulation and often the primary coagulation process as well.

In heterocoagulation, different dispersed systems mutually coagulate, resulting in particles of one dispersed phase adhering to particles of another phase. Heterocoagulation is enhanced by the mutual mixing of segregated salts with differently charged particle surfaces, since ionic electrostatic forces between them lead to attraction rather than repulsion.

The kinetics of Brownian motion in the coagulation of colloidal systems determine the required contact time of the flowing water interacting with the electrodes and the flow through the cells in the interelectrode space, such that the number of independent, unbound units is reduced by half, leading to the establishment of a “coagulation threshold” in contact time.

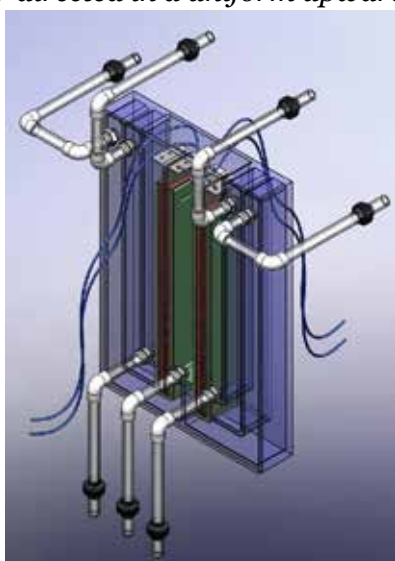
In the absence of an energy barrier, that is, at high current densities (for this invention approximately $4 A/dm^2$), $a = 1$; in the presence of an energy barrier, $a < 1$.

The residence time of the electrode cell in the interelectrode space in a system with a throughput of $1 m^3/hour$ is approximately

3 seconds. During this time, the entire volume of water passing through the electrode cell is subjected to the action of a spatial coagulating network.

For a water sample passing through the electrode cell approximately 0.2–0.6 seconds after leaving the interelectrode space, both from the anode and the cathode, the bulk density of the sample characterizes the initial turbidity, that is, the segregated dispersed medium (sediment).

Figure 6. *Electrochemical reactor housing with two parallel electrochemical cells, with water directed in a uniform upward flow*



The unstructured sediment phase formed within approximately 1–2 minutes transitions into a structured sediment phase and a consolidated sludge layer.

A candelabra-shaped (specifically, menorah-like) labyrinth configuration or form of the electrochemical reactor used in the W2W system provides a synchronized, electrochemically active and hydrodynamically stable environment for separating impurities from the flowing water.

To achieve optimal hydrodynamic synchronization of all parallel flows, the housing of the electrochemical reactor is filled with a labyrinth in the shape of a “menorah.”

This design allows for:

- placement of the electrochemical reactor in both horizontal and vertical orientations;
- stabilization of dynamic flow without additional energy consumption;

- synchronization of all incoming flows for each electrode cell;
- synchronization of parallel flow movement within the interelectrode space.

The movement and synchronization of contaminated water flows are schematically shown in Fig. 1, while the menorah-shaped labyrinth is shown in Fig. 2. The flowing water is divided into two equal parallel streams, driven by pressure in the range of approximately 1.2 to 1.5 bar.

As shown in the electrochemical reactor, the channels are equipped with openings directed toward the working chamber, while other openings are also oriented toward the working chamber. The primary and secondary working chambers are connected to adjacent channels, respectively. The channels of the two working chambers are interconnected by an opening. Since the operation of the chambers is identical, i.e., synchronized, hydrodynamic equilibrium can be considered for only one of them. The flow in one channel exits through an opening into an adjacent channel and reaches the working chamber.

Main structural characteristics of the electrochemical reactor:

- a labyrinth housing design in the form of a “menorah”;
- hydraulic connection between adjacent channels of the labyrinth;
- geometric and hydraulic symmetry between homogeneous elements of the reactor housing;
- presence of two electrode cells within the housing, identical in all structural and technological parameters;
- trapezoidal cross-section of electrode cells (in the case of flat-parallel electrodes, as an option) with parallel active working surfaces;
- self-sealing design of electrode cells;
- composite reactor housing;
- alternative spatial orientations of the housing;
- alternative electrode cross-sectional shapes;
- coaxial tubular electrodes (optional);
- two independent, identical DC power sources synchronized in all main parameters;

- symmetrical (optional) or asymmetrical (optional) positioning of active electrode surfaces;
- various configurations of interelectrode cross-sectional geometry;
- combined cathode and anode spaces within the interelectrode volume (optional);
- interconnected zones linked by adjacent symmetrical channels within the labyrinth;
- empirical relationship between the area of interconnected zones and the interelectrode cross-sectional area.

Empirical parameters:

The interelectrode space area is approximately 600 mm². The width of the active electrode surface is about 100 mm. The electrode cross-sectional area is approximately 200 mm². Preferred electrode materials include stainless steel, titanium, aluminum, iron, or carbon–carbon composites.

Main technological characteristics of the electrochemical reactor:

- stabilization and uniform distribution of water flow at the reactor inlet;
- gravitational stabilization and synchronization of flows entering the interelectrode space;
- synchronous passage of water streams through the interelectrode space within intersecting magnetic field lines under high voltage between active electrode surfaces;
- current supply from two synchronized, equivalent DC power sources, with doubling of either current or voltage through series or parallel synchronization combined with hydrodynamic stabilization;
- simultaneous parallel operation of oxidant/reductant generation and elec-

trochemically controlled dissolution (coagulant ion saturation) using a single energy supply mechanism;

- separate discharge of catholyte and anolyte (optional);
- sediment accumulation in settling tanks using hydrophobic enhancers and sedimentation elements, including sedimentation fibers, to increase settling rates over time.

Additional description of system operation:

The system for water treatment/purification/regeneration is applicable to both industrial and wastewater streams. The treated/regenerated water meets quality requirements for reuse in technological cycles.

Water treatment is carried out using an electrochemical method in which constant voltage is applied to adjacent electrodes, resulting in the formation of alkaline substances (at the anode) and acidic substances (at the cathode). Since water contains various contaminants and impurities, they react chemically with the electrochemically generated alkaline and acidic components.

The chemical reactions occurring in the flowing water near the electrodes are redox reactions. Thus, electrolysis consists of reduction at the cathode and oxidation at the anode.

The metal anode may be either (a) insoluble, serving only as a site for electron transfer during electrolysis, or (b) soluble (active), undergoing oxidation during the process.

The redox activity of the electric current often enhances oxidation and reduction reactions.

Analysis of standard electrode potentials shows that metal cations such as Cu²⁺, Hg²⁺, Ag⁺, Pt²⁺, and Pt⁴⁺, which have standard electrode potentials higher than hydrogen, are fully reduced during electrolysis, depositing either on or near the cathode.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-256-260



COMPOSITE DAIRY FOOD PRODUCTS. (Composite dairy food products as a result of an integrative innovative technological process)

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Cite: Skokova L. (2026). *Composite dairy food products. (Composite dairy food products as a result of an integrative innovative technological process). Austrian Journal of Technical and Natural Sciences 2026, No 5 – 6.* <https://doi.org/10.29013/AJT-26-5.6-256-260>

Abstract

As discussed in the article, various types of fermented dairy food composites and integrated food compositions that can be produced even under domestic conditions while ensuring high quality and sterility are considered. Particular attention is given to the development and practical application of an original device intended for whipping food composites, including composite butter.

The article describes an apparatus for whipping and homogenization of food compositions and composite butter designed for the efficient processing of fermented dairy raw materials, primarily sour cream or cream, including products with reduced fat content. The possibility of using preliminarily fermented raw materials and components is also examined.

Special emphasis is placed on the ability of the device to effectively process not only pure sour cream, but also sour cream compositions containing various additives, predominantly of plant origin. The article additionally considers the modification of composite butter through the introduction of vegetable fats during the whipping process in order to regulate the balance between vegetable and animal fats in the final product.

The design features of the apparatus make it possible to flexibly adapt the system for the production of butter and food composites with various additives and in different production volumes. The universality of the device and the possibility of rapid reconfiguration for the processing of multicomponent food compositions are highlighted as significant operational advantages.

The article also examines the structural configuration of the mixer flask consisting of three composite elements, including original engineering components that significantly influence the whipping process and the quality of the resulting commercial products.

Particular attention is devoted to the technological process of producing butter from multicomponent fermented dairy matrices with varying fat content. The described process includes the sequential introduction of dairy and plant-based components into the mixer flask, hermetic sealing of the working chamber, installation of the mixer flask into the drive system, and con-

trolled positioning of the rotational axes during the whipping process.

Such an approach makes it possible to create multifunctional food-processing systems intended for the production of innovative composite dairy products with improved technological and nutritional characteristics.

Keywords: *Food products, Dairy food products, Composite dairy food products, Fermented dairy food products, Device for whipping food composites, Device for whipping food composites, including composite butter, Description of the original apparatus and principles of its practical application, Apparatus for whipping and homogenization of food compositions, Apparatus for whipping and homogenization of food compositions and composite butter, The apparatus is intended for the efficient whipping of these complex products from fermented dairy raw materials, Fermented dairy raw materials, primarily sour cream or cream, predominantly with low fat content, Initial products or components may be preliminarily subjected to fermentation, Possibility of efficient whipping of the product not only from pure sour cream, but also from sour cream with various additives, mainly of plant origin, Possibility of modification of composite butter through the introduction of vegetable-origin fats during the whipping process in order to change the balance of vegetable and animal fats in the butter*

Introduction

Principal differences of the whipping process for a food composite based on butterfat compositions compared to existing processes of similar purpose:

- the whipping process is carried out in a flask having the shape of a cylinder closed at both ends by hemispherical covers equipped with axial conical openings;
- the entire flask structure, consisting of a cylindrical shell with conical edge surfaces and two hemispherical covers having conical chamfers at their bases and coaxial conical openings along the axis, is assembled and hermetically sealed by introducing fixing and sealing elements into the conical openings of the covers previously aligned with the cylindrical shell through corresponding conical surfaces; these elements perform clamping, orientation, fixation, and sealing functions for the internal volume of the structure;
- due to these structural features, the whipping process obtains not only formal structural distinctions, but also significant technological advantages reflected in the quality of the final product and in the expansion of the technological capabilities of the butter-whipping process;
- the whipping chamber is designed as a detachable and reconfigurable structure;
- during the whipping process, controlled access to the internal volume is possible for the introduction of components, removal of waste products, or extraction of part of the processed composition;
- the conical openings of the hemispherical covers contribute to a more effective fragmentation and homogenization of the mixture during impact against the internal hemispherical surfaces, simultaneously performing activating, orienting, sealing, fixing, and technological gateway functions;
- the described construction makes it possible to use several interchangeable flask assemblies within one whipping apparatus, enabling rapid changes in the composition of the whipped mixture, including the characteristics and fat content of the fermented dairy matrix;
- hydrodynamic parameters of the whipping process are substantially improved due to the geometric configuration of the flask elements and the transformation of the whipped mass from cylindrical to spherical form during impact interactions;
- the described impact mechanism creates a kinetic diversity of forced changes in the volume and geometric configuration of the whipped mass under the influence of multiple force factors generated by the geometry of the flask and the kinematics of the whipping apparatus.

The photo shows some of the many different types of fermented dairy food composites and integrated food composites that can be produced even under domestic conditions while ensuring high quality and sterility.

Photo 1.



The presented testing results of the hemispherical cover models demonstrate that:

- their construction is technologically efficient;
- they possess high mechanical strength;
- they are convenient for maintenance;
- they satisfy hygienic requirements;
- they may be manufactured from various materials;
- different variants of hemispherical covers may be used with the same cylindrical shell configuration while preserving the compatibility of all connection elements.

Device for whipping food composites, including composite butter – description of the apparatus and principles of practical application.

The apparatus for whipping and homogenization of food compositions and composite butter is intended for the efficient processing of complex products based on fermented dairy raw materials, primarily sour cream or cream, including products with reduced fat content. Initial products and components may be preliminarily subjected to fermentation.

Preliminary testing demonstrated the possibility of efficient whipping not only of pure sour cream, but also of sour cream com-

positions containing various additives predominantly of plant origin.

Such additives may include:

- carrot juice;
- carrot puree or paste;
- tomato juice;
- tomato paste;
- cucumber brine;
- cucumber puree;
- avocado puree;
- kiwi puree;
- sweet pepper puree;
- various zucchini purees;
- fruit purees including apple, plum, peach, pear, apricot, pineapple, and tropical fruit and vegetable purees;
- combinations of the listed additives with dill, garlic, onion, and lemon;
- prune pulp;
- preserves made from chokeberry, sea buckthorn, and other medicinal berries;
- berry purees including strawberry, wild strawberry, blueberry, blackcurrant, raspberry, mulberry, viburnum, gooseberry, and others.

The above list may be expanded through the use of fruits and vegetables from different geographical regions in various combinations.

Modification of composite butter is possible through the introduction of vegetable fats during the whipping process in order to regulate the balance between vegetable and animal fats in the final product.

To expand the application range of the butter-whipping device, its design allows flexible reconfiguration for the production of butter compositions with different additives and in various production volumes.

The versatility of the apparatus, including the possibility of rapid reconfiguration for whipping composite butter with different components, constitutes one of its principal operational advantages.

The mixer flask consists of three structural elements, among which the following components exert the greatest influence on whipping efficiency and the characteristics of the resulting commercial products:

- the cylindrical shell of the mixer flask containing conical recesses for hermetic sealing, centering, and volumet-

ric orientation of the flask geometry within three-dimensional space;

- the upper hemispherical cover containing two coaxial conical surfaces intended for centering, orientation, and sealing of the internal flask volume while allowing the introduction of components through the axial fixation system;
- the lower hemispherical cover containing three coaxial conical surfaces intended for centering, orientation, sealing, and removal of technological waste products generated during the whipping process.

The process of producing high-quality homogenized butter without additives includes the following operations:

After cleaning from the previous production cycle, the flask and hemispherical covers are preliminarily aligned along the conical surfaces, mounted within the frame, and compressed axially until complete alignment of all conical interfaces is achieved.

The required volume of sour cream or fermented cream is then introduced into the internal volume of the flask through the upper fixation system.

The sealing plug is closed and rotation of the frame with the flask is initiated. The sour cream moves along the internal axis of the flask and impacts the hemispherical covers during each half-rotation of the frame.

After completion of the whipping cycle, the system is stopped, the flask is positioned vertically, and the lower valve is opened for removal of technological by-products formed during the whipping process.

The fixation systems are then released, the flask is removed, the covers are detached, and the whipped butter is extracted from the cylindrical shell. The three structural components are subsequently cleaned and replaced with a new interchangeable set.

When additives or additive combinations are required, all components are introduced according to the described technological scheme.

The possibility of flexible introduction of components depending on process time, product readiness, temperature changes, or chemical-technological indicators substantially expands the operational and technological capabilities of the apparatus.

Process and apparatus for whipping animal composite butter from multicomponent raw materials containing plant-based and animal-origin components integrated into a fermented dairy matrix in various proportions:

The invention relates to a process for whipping animal butter predominantly from multicomponent raw materials based on a fermented dairy matrix with any fat content, including reduced fat content.

The process includes:

- formation of the initial material within the internal volume of the mixer flask through sequential introduction of the fermented dairy matrix and plant-based and animal-origin additives;
- installation of the mixer flask into the drive frame and hermetic sealing of the internal volume through axial fixation of the hemispherical covers;
- mounting of the drive frame within the rotating support structure while maintaining a defined angle between the axis of the flask and the axis of spindle rotation throughout the whipping process;
- reciprocating movement of the processed material along the flask axis with periodic impact interaction against the hemispherical surfaces during each half rotation of the spindle system;
- repeated reversal of the movement direction of the processed material;
- accumulation of kinetic energy during each change in movement direction;
- removal of technological waste products;
- depressurization and removal of the flask from the frame;
- removal of the hemispherical covers and extraction of the whipped product from the cylindrical shell.

The apparatus for whipping animal butter from multicomponent raw materials based on a fermented dairy matrix and plant-based and animal-origin additives consists of permanent and interchangeable elements. Permanent elements include spindles mounted within a drive bracket and connected to a mixer drive frame. The cylindrical shell of the mixer flask contains conical recesses into

which corresponding conical protrusions of the hemispherical covers are inserted.

The apparatus for whipping animal butter from a fermented dairy low-fat matrix with plant-based and animal-origin additives includes permanent and interchangeable elements connected through rotational and reciprocating kinematic mechanisms.

The described process involves repeated impact interaction of the multicomponent mixture with hemispherical surfaces limiting the internal cylindrical volume of the detachable flask. The reciprocating movement and kinetic acceleration continuously change direction relative to the rotational phase of the detachable mixer flask.

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submitted 22.04.2026;
accepted for publication 05.05.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-261-270



QUANTUM TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE. (Practical Applications of Quantum Technologies in Combination with Artificial Intelligence)

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Cite: Ostap Victor Vlad. (2026). *Quantum Technologies and Artificial Intelligence. (Practical Applications of Quantum Technologies in Combination with Artificial Intelligence)*. Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-261-270>

Abstract

This article examines the practical application of artificial intelligence technologies in combination with machine learning algorithms, artificial neural networks, and emerging quantum technologies for solving complex engineering, analytical, and decision-support tasks. Particular attention is devoted to the interaction between artificial intelligence and human expertise, demonstrating that modern AI systems function most effectively as intelligent decision-support tools under professional supervision rather than as complete substitutes for highly qualified specialists.

The publication analyzes contemporary machine learning models capable of predicting human decision-making under conditions of uncertainty and risk. Special emphasis is placed on behavioral prediction models that integrate established behavioral science theories with machine learning techniques to improve the accuracy of forecasting human choices and optimize decision-support systems in engineering, economics, management, and other applied fields.

Keywords: *Artificial Intelligence; Artificial Neural Networks; Quantum Technologies and Solutions; Fields of Application; Machine Learning Algorithm; Artificial Intelligence Mechanism; Conventional Information Storage Systems; Documents for Instant Access; Machine Learning Model; Capability to Predict Human Decision-Making; Mathematical Formula; Engineering Design of Quantum Dots*

Introduction

Although artificial intelligence is currently unable to fully replace qualified specialists in any field of application, it is already capable of displacing entry-level professionals who perform preliminary or routine work, provided that the final refinement, supervi-

sion, and quality control remain the responsibility of an experienced specialist.

For example, a modern chatbot can already perform many tasks typically assigned to a junior programmer by generating code in a specified programming language and for a defined technical purpose. However,

a qualified professional is still required to design the overall project architecture, supervise and guide the AI during task execution, coordinate files and functions within the project, separate backend and frontend components, and ensure the integrity of the final software system.

Therefore, in order to remain competitive with artificial intelligence in creative and intellectual professions, people will need to develop precisely those skills that still distinguish human specialists from machines: the ability to build abstractions, integrate separate components into a coherent whole, test solutions, identify and correct errors, introduce stylistic diversity, and enrich creative work with originality and contextual meaning.

The artificial intelligence system Grok, integrated into the social network X, has recently received a function for animating images. At the present stage, this feature is operating in a test mode and is available only to paid subscribers of the former Twitter platform.

Since the number of such subscribers is significant, the first examples of generated content have already begun to appear online. Some of the most impressive results have been shared by Elon Musk, the American entrepreneur and owner of the social network.

Grok has learned to animate various types of images, including photographs of people. This is not the first technology of its kind, as similar tools already exist, including services such as Midjourney and Google's video generation system Veo 3. However, such services are relatively expensive, and the ability to generate video directly from images within the social media ecosystem may become an important additional advantage for users.

The rapid development of artificial intelligence has significantly accelerated the transition from text-based information to visual content. Today, the generation of high-quality images from textual descriptions and the creation of realistic videos based on still images are becoming increasingly widespread and are transforming the way digital information is produced and consumed.

Digital platforms capable of providing such services on a large scale are expected to gain substantial competitive advantages by attracting new users and expanding their technological ecosystems. Although

this trend will inevitably evolve as new technologies emerge, visual artificial intelligence currently represents one of the most dynamic directions in the development of modern information technologies.

While considerable public attention remains focused on large language models such as ChatGPT and similar systems, a fundamental technological transformation is simultaneously taking place within the infrastructure supporting artificial intelligence. Modern approaches to storing, indexing, and processing unstructured information – including documents, images, video, and multimedia datasets – are undergoing a profound evolution. One of the leading technological developments in this field is represented by intelligent semantic data storage systems that enable artificial intelligence platforms to process extremely large volumes of heterogeneous information with unprecedented speed and efficiency.

Unlike conventional information storage systems that rely primarily on file names, directory structures, and keyword indexing, modern intelligent storage architectures automatically analyze the semantic content of stored information and generate vector representations describing its meaning. As a result, information retrieval is performed according to semantic similarity rather than exact textual coincidence, allowing intelligent systems to locate relevant documents and datasets even when identical keywords are absent.

An equally important direction in the practical application of artificial intelligence involves the prediction of human decision-making under conditions of uncertainty and risk. Understanding the mechanisms governing human decisions remains one of the principal challenges of contemporary behavioral science and has significant implications for economics, engineering, management, healthcare, and public policy.

Recent advances in machine learning have demonstrated that behavioral prediction models combining artificial intelligence algorithms with established theories of behavioral science can achieve exceptionally high prediction accuracy. Models based on integrated behavioral characteristics transform psychological decision-making strategies into mathematical representations suitable for ma-

chine learning algorithms. Such approaches allow artificial intelligence systems to identify stable behavioral patterns and predict human decisions even when operating with previously unseen datasets, demonstrating a high degree of generalization.

The practical significance of these technologies extends far beyond behavioral analysis. Predictive artificial intelligence systems are increasingly applied to decision-support systems, intelligent control platforms, adaptive engineering solutions, financial forecasting, medical diagnostics, autonomous transportation, and complex industrial processes where reliable prediction of human behavior substantially improves the effectiveness of operational and strategic decision-making.

Artificial intelligence technologies are also becoming increasingly important in solving global engineering and environmental challenges. One example is the development of advanced membrane technologies for water desalination. Recent scientific investigations have demonstrated that the structural and transport properties of desalination membranes under fully hydrated operating conditions differ significantly from those observed in conventional dry-state laboratory testing. These findings provide new opportunities for improving membrane performance, increasing freshwater production efficiency, and reducing the energy consumption of desalination systems.

Considering that approximately one-quarter of the world's population continues to lack reliable access to safe drinking water, the integration of artificial intelligence, advanced materials science, intelligent process control, and modern engineering technologies represents one of the most promising directions for achieving sustainable water management and supporting the global objectives of environmental protection and sustainable development.

Israel is currently recognized as one of the world's leading countries in both water purification and seawater desalination technologies. The country's five large-scale desalination plants provide approximately 70% of Israel's domestic water supply, while nearly 85% of municipal wastewater is treated and subsequently reused for agricultural irrigation.

The principal technology employed for both desalination and water purification is reverse osmosis. During this process, saline water or water requiring purification is forced through ultra-thin membranes whose pore sizes are smaller than one nanometer. To achieve effective separation, the feed water must be supplied under extremely high pressure, making reverse osmosis a highly energy-intensive process. A single large desalination facility may consume an amount of electrical energy sufficient to supply a small city.

Researchers working on reverse osmosis technologies have long recognized that membrane performance should be evaluated under actual hydrated operating conditions. However, because both the membrane pores and their internal structures are at the nanometer scale, direct observation had remained technically impossible for many years. This limitation has recently been overcome by freezing the water contained within the membrane structure and examining the hydrated membrane using cryogenic transmission electron microscopy (cryo-TEM), allowing its operational microstructure to be investigated under realistic working conditions.

Practical investigations have further demonstrated that the integration of membrane filtration systems with electrochemical reactors into a single treatment module, combined with an upward parallel-flow water treatment system functionally connected through automatic mechanical filtration units, provides significantly higher water purification efficiency and improved treatment performance compared with conventional water treatment technologies.

The figure illustrates such integrated comprehensive water-treatment modules, which demonstrate superior water regeneration quality, higher processing efficiency, and substantially faster regeneration rates than traditional water treatment systems.

Researchers demonstrated that water fundamentally alters the internal structure of reverse osmosis membranes. Under operating conditions, hydrated membranes expand by approximately one-third or more, resulting in significant changes to their three-dimensional architecture, including the size and geometry of nanopores. These findings provide engineers with a new scientific basis

for improving reverse osmosis systems. Considering the global importance of water desalination and purification technologies, even modest improvements in membrane ef-

iciency or reductions in operating pressure may result in substantial energy savings and significant economic benefits.

Figure 1.



Researchers at the Hebrew University of Jerusalem have proposed new quantum cryptography protocols capable of operating reliably even with imperfect hardware. Quantum cryptography has long been regarded as one of the most promising approaches for achieving theoretically unbreakable secure communications. However, its widespread implementation has been limited by the requirement for highly stable single-photon sources, which remain technically complex and expensive.

Instead of relying on ideal photon emitters, the researchers developed a protocol compatible with currently available quantum-dot-based light sources that behave similarly to artificial atoms. Engineering optimization of quantum dots, combined with specially designed nanoscale optical antennas, enabled precise control of emitted light pulses. The proposed approach is based on the purification of an initially “noisy” optical signal, whereby multiple emitted photons are filtered in real time, allowing only high-quality single photons suitable for quantum key distribution to enter the communication channel.

To validate the proposed concept, the research team constructed a room-temperature

quantum-dot system and successfully tested an adapted quantum cryptographic protocol. Experimental results demonstrated reliable quantum key exchange despite the use of non-ideal photon sources. According to the authors, the proposed technology is compatible with a broad range of quantum light sources and therefore represents a practical pathway toward the large-scale deployment of secure quantum communication networks.

Another significant achievement has been reported by researchers from the Technion – Israel Institute of Technology, who developed the BEAST-GB machine learning model capable of predicting human decision-making under conditions of uncertainty and risk with an accuracy approaching 96%.

Understanding human decision-making remains one of the central challenges of behavioral science. Accurate prediction of human choices has important applications in economics, engineering, healthcare, public administration, and intelligent decision-support systems.

The BEAST-GB model integrates machine learning algorithms with established theories of behavioral science. It is based on the BEAST (Best Estimate and Sam-

pling Tools) behavioral framework, which combines psychological theories describing how individuals evaluate uncertain alternatives. Human behavioral strategies were transformed into mathematical behavioral characteristics representing sensitivity to specific decision variables. These mathematically defined characteristics, supplemented by objective descriptions of decision-making tasks, were subsequently incorporated into machine learning algorithms.

The resulting model demonstrated the ability to explain and accurately predict human decisions across a wide range of previously unseen scenarios with approximately 96% prediction accuracy, substantially outperforming conventional behavioral models that typically achieve prediction rates of only 30–50%. The model's ability to generalize beyond its training data indicates that it successfully captures universal behavioral patterns governing human decision-making.

The continuing expansion of artificial intelligence infrastructure is further illustrated by the development of SDS-AI, a new national supercomputing platform being deployed by Shonfeld Data Services (SDS). Built on NVIDIA Blackwell B200 processors, the system incorporates 2,032 next-generation processors and is expected to achieve computational performance approximately 6.5–6.8 times greater than the existing Israel-1 supercomputer.

Unlike previous high-performance computing systems designed primarily for internal corporate applications, SDS-AI has been developed as an open computational platform intended to support Israel's innovation ecosystem. The supercomputer will provide advanced computational resources to startups, universities, research institutions, and technology companies, enabling the domestic development of next-generation artificial intelligence systems without reliance on foreign computing infrastructure.

One of the most promising practical applications of artificial intelligence is the development of the Smart Specialist's Office concept. This integrated digital environment combines intelligent clinical management software, electronic medical records, mobile applications, diagnostic support systems, and artificial intelligence algorithms

into a unified platform. Such systems assist medical specialists in diagnostics, treatment planning, workflow optimization, clinical decision support, and healthcare resource management, thereby improving both the quality of patient care and the overall efficiency of modern medical institutions.

One of the most promising practical applications of artificial intelligence is the development of the Smart Physician's Office concept, which represents an integrated digital environment designed to improve the efficiency of medical diagnostics, treatment planning, and healthcare management. Rather than replacing physicians, artificial intelligence functions as an intelligent clinical assistant, supporting medical professionals in data analysis, image interpretation, clinical decision-making, and workflow optimization.

A modern smart physician's office integrates several complementary technological components into a unified information ecosystem.

The first component consists of intelligent medical information systems. Specialized software platforms enable healthcare institutions to manage patient databases, electronic medical records, appointment scheduling, clinical documentation, treatment planning, and administrative processes. Such systems substantially improve operational efficiency while reducing the probability of human error.

The second component includes mobile medical applications developed for both physicians and patients. These applications support clinical diagnostics, treatment planning, educational activities, remote consultation, and professional communication. Specialized software can also assist physicians in analyzing clinical findings, monitoring patient conditions, and developing individualized preventive recommendations.

A third essential component is the integration of artificial intelligence technologies into clinical practice. AI systems are capable of analyzing medical images, identifying pathological changes, supporting differential diagnosis, evaluating treatment outcomes, and assisting physicians in preparing individualized treatment strategies. Although these systems significantly improve diagnostic accuracy and decision support, they complement rather than replace professional medical judgment.

The fourth technological component comprises advanced digital medical equipment. Modern digital radiographic systems, intraoral scanners, three-dimensional imaging systems, high-resolution optical cameras, and computer-controlled therapeutic equipment provide highly accurate diagnostic information while improving patient comfort and reducing examination time.

The implementation of smart medical technologies provides numerous practical advantages. Digital diagnostic systems improve the accuracy and reliability of clinical examinations, while intelligent information systems optimize medical workflows, automate routine administrative operations, and reduce the likelihood of procedural errors. Integrated communication platforms facilitate interaction between healthcare professionals and patients, improving treatment coordination and continuity of care. Furthermore, the adoption of advanced digital technologies contributes to the establishment of a modern, technologically advanced healthcare environment capable of delivering higher-quality medical services.

The continuing integration of artificial intelligence, advanced medical software, intelligent diagnostic equipment, and automated clinical management systems demonstrates the ongoing transformation of healthcare toward comprehensive digital ecosystems in which engineering technologies, information systems, and medical expertise operate as a unified intelligent platform for improving clinical effectiveness and patient outcomes.

Quantum dots are ultra-small semiconductor particles whose dimensions are tens of thousands of times smaller than the diameter of a human hair. Since their introduction, their unique physical properties – providing the highest levels of color accuracy, brightness, and spectral purity among currently available display materials – have transformed modern display technologies.

When incorporated into display panels, quantum dots provide an exceptionally wide color gamut corresponding closely to the full spectrum perceived by the human eye. They also enable highly accurate pixel-level light control, resulting in improved black-level reproduction, greater contrast, and superior overall image quality.

Because quantum dots emit light uniformly in all directions, they ensure consistent brightness and stable color reproduction regardless of viewing angle while simultaneously minimizing blue-light emission, thereby improving visual comfort during prolonged viewing.

The commercial performance of quantum-dot displays is determined by several important engineering parameters, including the concentration of active quantum-dot material, the quality and structural uniformity of the quantum-dot film, and the application of environmentally safe cadmium-free quantum-dot technologies. High-performance displays generally require quantum-dot concentrations exceeding approximately 3,000 parts per million (ppm) in order to achieve the characteristic brightness, color saturation, and image fidelity associated with this technology.

The year 2025 has become a significant milestone in technological development, marking the transition of numerous long-term scientific achievements from laboratory research to practical industrial implementation. Major advances have occurred simultaneously in artificial intelligence, quantum technologies, advanced computing, robotics, energy systems, and space technologies, substantially influencing global industrial competitiveness and economic development.

Artificial intelligence has emerged as one of the principal driving forces behind this technological transformation. Generative AI technologies have evolved beyond experimental systems and are now being integrated into governmental institutions, industrial enterprises, healthcare systems, engineering platforms, and commercial organizations, where they automate complex workflows while creating entirely new categories of products and services.

At the same time, the United Nations designated 2025 as the International Year of Quantum Science and Technology, emphasizing the strategic importance of quantum research worldwide. Commercial and academic organizations continue to demonstrate steady progress in quantum computing, including the development of topological quantum processor architectures and advanced quantum simulation systems, bringing prac-

tical quantum computing significantly closer to industrial deployment.

Another major technological breakthrough has occurred in controlled nuclear fusion research. Several research laboratories have successfully demonstrated fusion systems capable of producing energy outputs exceeding the energy required to sustain the fusion reaction while maintaining stable operating conditions for longer durations than previously achieved. These advances represent important milestones toward the future commercialization of fusion power generation.

Rapid progress is likewise being observed in intelligent robotics and autonomous systems. Advanced computing platforms integrating artificial intelligence into autonomous robotic systems are enabling industrial robots to perform increasingly complex operations independently across manufacturing, logistics, transportation, mining, and infrastructure management.

Space technologies continue to demonstrate remarkable advances through increasing launch frequencies, lunar exploration programs, on-orbit satellite servicing technologies, and autonomous spacecraft operations, illustrating the growing maturity of modern aerospace engineering.

Collectively, these developments demonstrate that artificial intelligence, quantum technologies, advanced semiconductor materials such as quantum dots, intelligent robotics, high-performance computing, sustainable energy technologies, and space engineering are becoming mutually integrated components of a new global technological ecosystem. Their convergence is expected to establish the technological foundation for future industrial infrastructures, intelligent manufacturing systems, secure communication networks, advanced healthcare platforms, and next-generation digital economies.

The modern world can no longer be imagined without artificial intelligence, which has rapidly become an integral component of everyday life. AI technologies are now widely used to optimize professional activities, automate routine operations, support scientific research, and solve numerous everyday tasks. Moreover, many people interact with artificial intelligence systems on a daily basis without even realizing it. Nevertheless,

the full extent to which artificial intelligence is transforming the technological, economic, and social foundations of modern civilization has yet to be fully appreciated.

Although the fundamental concepts underlying artificial neural networks were proposed more than fifty years ago, practical implementation became possible only after the emergence of sufficiently powerful computing systems capable of processing enormous volumes of information. The operation of modern artificial intelligence systems relies primarily on computationally intensive mathematical processing, pattern recognition, statistical optimization, and large-scale machine learning algorithms. Consequently, further progress in artificial intelligence remains closely linked to advances in high-performance computing technologies.

The continuing development of artificial intelligence is increasingly constrained by the availability of computational resources and electrical energy. The performance of advanced language models and intelligent systems depends directly on the computational capacity of modern data centers equipped with next-generation processors. These facilities consume substantial quantities of electrical power, and projections indicate that artificial intelligence infrastructure will become one of the largest industrial consumers of energy over the coming decade.

An equally important strategic factor is the availability of advanced engineering materials required for manufacturing high-performance computing equipment. Semiconductor devices, graphics processors, memory systems, and data-center infrastructure require significant quantities of silicon, copper, rare-earth elements, cobalt, neodymium, praseodymium, manganese, and numerous other critical materials. Consequently, the availability of these resources has become an essential determinant of technological competitiveness and national economic security.

Artificial intelligence is simultaneously transforming modern healthcare. One notable example is the development of intelligent diagnostic systems capable of evaluating coronary artery disease using conventional X-ray angiographic images. Recent advances in machine learning have enabled artificial intelligence models to estimate the

physiological severity of arterial stenosis without requiring invasive diagnostic procedures involving pressure-sensing guidewires and pharmacological stimulation.

Such intelligent diagnostic systems significantly reduce procedural risks while providing physicians with reliable clinical information in real time. By integrating artificial intelligence into routine cardiological practice, healthcare providers can improve diagnostic accuracy, optimize therapeutic decision-making, personalize treatment strategies, and enhance overall patient safety. These technologies have already been successfully applied in the clinical evaluation of more than one hundred thousand patients, demonstrating their practical effectiveness and medical value.

Another rapidly developing research area concerns the creative capabilities of generative artificial intelligence. Recent comparative investigations involving large language models – including ChatGPT, Claude, Gemini, and other advanced systems – have demonstrated that modern AI models are capable of outperforming the average human participant in standardized assessments of divergent linguistic creativity.

These studies indicate that contemporary generative artificial intelligence has achieved a level of creative performance exceeding the average results obtained from large human populations. Nevertheless, the highest levels of originality, conceptual abstraction, and creative diversity remain uniquely associated with exceptionally creative individuals. Psychological testing based on Divergent Association Tasks has confirmed that although artificial intelligence can successfully generate diverse and innovative ideas, the most outstanding human creative abilities continue to surpass those of even the most advanced large language models.

The convergence of artificial intelligence, high-performance computing, advanced semiconductor technologies, intelligent medical systems, and computational creativity demonstrates the emergence of a new technological paradigm in which engineering, information technologies, and machine intelligence operate as an integrated ecosystem. Continued advances in computational infrastructure, energy technologies, critical

materials engineering, and intelligent algorithms will determine the future pace of innovation and the practical implementation of next-generation artificial intelligence systems across science, medicine, industry, and society.

One widely used assessment of creative thinking is the Divergent Association Task (DAT), in which participants – whether humans or artificial intelligence systems – are asked to generate ten words that are as semantically unrelated as possible. A highly creative response might include words such as *galaxy, fork, freedom, algae, harmonica, quantum, nostalgia, velvet, hurricane, and photosynthesis*. The DAT has demonstrated strong consistency with other validated methods used to evaluate creativity in idea generation, creative writing, and problem-solving. Although the test is language-based, it measures not merely vocabulary but a broad range of cognitive processes underlying divergent thinking. An additional advantage of the DAT is its simplicity and accessibility, requiring only two to four minutes to complete and being readily available online.

Building upon these findings, researchers investigated whether the ability of artificial intelligence to perform well on relatively simple word-association tasks could be transferred to more complex creative activities. Large language models were directly compared with human participants in creative writing exercises, including the composition of haiku poetry, short film plot summaries, and original short stories. The results confirmed the same general tendency observed in the DAT assessment. While artificial intelligence occasionally outperformed average human participants, the most experienced and highly creative authors consistently maintained a substantial advantage.

According to the latest global survey conducted by McKinsey & Company, approximately 88% of organizations worldwide are expected to have implemented artificial intelligence in at least one business function by the end of 2025. However, recent research published in *Scientific Reports* indicates that the use of artificial intelligence in the workplace may produce not only organizational benefits but also important psychological consequences for employees.

The study demonstrated that passive use of artificial intelligence – where employees simply copy and paste AI-generated responses – may reduce confidence in their own professional abilities and diminish the perceived significance of their work. Approximately 270 professionals from various fields, including human resources, management, and communications, participated in the investigation. Participants completed writing tasks representative of their daily professional activities under three different conditions: independently, collaboratively with artificial intelligence, or by directly adopting AI-generated responses.

The results demonstrated that the manner in which artificial intelligence is utilized significantly influences employees' psychological state. Passive AI usage reduced personal responsibility for work outcomes by nearly 20%, while self-efficacy and perceived work meaningfulness declined by approximately 10%. In contrast, participants who actively collaborated with artificial intelligence as an intelligent assistant exhibited psychological indicators almost identical to those observed among individuals completing tasks independently.

Researchers evaluated three principal psychological variables: self-efficacy, defined as confidence in one's ability to perform tasks without artificial intelligence; perceived meaningfulness of work; and psychological responsibility for task outcomes. Additional measures included overall satisfaction with both the work process and the final results.

The experimental design consisted of two consecutive stages. During the first stage, participants completed tasks either independently, through active collaboration with artificial intelligence, or by passively copying AI-generated content. During the second stage, all participants performed similar tasks without any artificial intelligence assistance. This methodology enabled researchers to evaluate both immediate and longer-term psychological effects.

The findings revealed that the negative consequences associated with passive artificial intelligence usage persisted even after participants returned to independent work. Individuals continued to report lower confidence in their own abilities and reduced

perceptions of the value of their professional contributions. Although passive AI usage initially increased task satisfaction by as much as 29% compared with completely manual work, this advantage disappeared over time. When participants resumed independent work, their satisfaction with both the work process and its outcomes declined below that observed among individuals who had never relied on artificial intelligence.

According to the researchers, these effects arise because employees rapidly become accustomed to the ease with which artificial intelligence completes complex tasks and subsequently begin to perceive their own expertise as less valuable. As AI systems demonstrate increasing competence, concerns regarding personal replaceability become more pronounced. The authors therefore emphasize that organizations should not merely deploy artificial intelligence technologies but should also train employees to interact with them actively and constructively, thereby preserving professional competence, motivation, and long-term engagement.

Another strategic direction in modern artificial intelligence research concerns the development of scalable quantum computing architectures. One of the principal engineering challenges in this field is the design of quantum computer architectures capable of supporting millions of stable qubits while maintaining reliable quantum coherence and efficient error correction.

An example of this approach is the start-up Q-Factor, founded by researchers from the Weizmann Institute of Science and the Technion – Israel Institute of Technology. The company is developing a neutral-atom quantum computing architecture designed to scale toward one million qubits and has already secured approximately US\$24 million in seed investment.

Neutral-atom quantum computing employs individual atoms suspended in vacuum using optical laser tweezers. Unlike superconducting quantum computers, which require extremely low operating temperatures and highly complex cryogenic infrastructure, neutral atoms are naturally identical, free from manufacturing defects, and well isolated from external electromagnetic disturbances. These characteristics provide excellent

conditions for preserving quantum information while allowing extremely high qubit densities within compact physical volumes.

The principal innovation introduced by Q-Factor addresses one of the fundamental bottlenecks in scalable quantum computing: laser control. Rather than employing millions of independent laser emitters, the proposed architecture utilizes a single high-power laser beam directed through a programmable spatial light modulator functioning as a dynamic holographic optical array. This device divides the original beam into hundreds of

thousands of precisely controlled microscopic optical traps capable of simultaneously manipulating large arrays of neutral atoms.

Such an architecture substantially simplifies quantum control, improves error-correction capabilities, and enables future quantum computers to solve computational problems beyond the reach of even the world's most powerful classical supercomputers, including molecular simulation for pharmaceutical development, optimization of global logistics systems, advanced materials design, and large-scale engineering optimization.

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submitted 15.06.2026;
accepted for publication 29.06.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-271-275



**INVENTIVE PROBLEMS AND MODERN THEORIES AND REAL-
WORLD PRACTICE OF COMMERCIALIZATION.
(Integration and psychological adaptation of the Theory and
Algorithm for Inventive Problem Solving with modern theories
and real-world commercialization practices, implemented and
systematically adapted to the parameters and initial requirements
of contemporary high-technology projects through the application
of elements of artificial intelligence and artificial neural networks)**

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Cite: Vorobiova K. (2026). *Inventive problems and modern theories and real-world practice of commercialization. (Integration and psychological adaptation of the Theory and Algorithm for Inventive Problem Solving with modern theories and real-world commercialization practices, implemented and systematically adapted to the parameters and initial requirements of contemporary high-technology projects through the application of elements of artificial intelligence and artificial neural networks). Austrian Journal of Technical and Natural Sciences 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-271-275>*

Abstract

As discussed in the article, the integration and adaptation of the Theory and Algorithm for Inventive Problem Solving (TRIZ and ARIZ) with modern theories and real-world commercialization practices are examined. Particular attention is devoted to the influence of technical stereotypes and psychological barriers on the generation, evaluation, and implementation of innovative technical solutions within contemporary high-technology projects. The article analyzes the distinction between practical inventions that effectively solve real engineering and technological challenges and conceptual solutions that remain detached from actual market and industrial needs. The role of innovation analysis in identifying commercially viable technical concepts and overcoming technical and technological contradictions is also considered.

Special emphasis is placed on the changing requirements imposed on inventors by rapid technological progress, shortened product development cycles, increasing prototype costs, and the growing complexity of modern engineering systems. The article highlights the importance of multidisciplinary competencies, market awareness, and the ability to combine technical creativity with commercialization strategies.

The integration of forecasting techniques, innovation methodologies, artificial intelligence, and artificial neural network technologies is presented as an essential component of modern inventive activity. Such an approach enables inventors to develop technically sound, commercially relevant, and practically implementable solutions while reducing the influence of psychological

barriers and improving the effectiveness of innovation processes.

The article demonstrates that successful commercialization of innovative ideas increasingly depends on the inventor's ability to synthesize technical knowledge, market requirements, and advanced analytical methods into a unified framework for the development and implementation of high-value technological solutions.

Keywords: *Integration; Adaptation; Modern theories and real-world commercialization practices; Commercialization parameters and implementation practices; Innovation analysis; Artificial intelligence and artificial neural networks; Obvious technical solutions; Engineering and technology; Purposeful creative activity; Realization of ambitious integrated objectives; Technical stereotypes; Overcoming technical and technological contradictions; Forecasting techniques; Implementation of synthesized ideas*

Introduction

There are several fundamental directions that, under current conditions, have a decisive influence on the fate of new ideas. Taking these directions into account may ensure a real and high level of commercial success, whereas neglecting them may permanently close the path for an idea to be implemented in any commercial form.

The author proposes to consider some of these fundamental directions (naturally, the scope of this article allows this to be done only in the form of theses).

For modern technological innovations, which are largely formed through active and intensive brainstorming involving a sufficiently large team or group of specialists interested, to one degree or another, in achieving an effective result that may, in principle, be considered the equivalent of an ideal final result, there exist real problems in organizing the innovation process. These problems are caused by objective factors, including psychological, technological, and design stereotypes, as well as the apparent obviousness of emerging ideas and concepts.

The technical, compositional, and technological solutions that emerge and continue to emerge are evaluated and considered through the prism of conclusions derived from the practical application of the laws governing the development and construction of industrial technologies, machines, and mechanisms that originated at least in the previous century, at a time when none of the modern materials, components, assemblies, industrial electronics, and laser technologies known today existed.

In addition, the integration of elements of artificial intelligence and artificial neural networks into the infrastructure of new

technical systems greatly complicates the processes of designing and forming the technical and technological characteristics of innovative products.

This situation is further aggravated by the fact that, as stated in the first part of this publication, recognition of a technical solution as an invention is based in the United States and in most other countries on different criteria: in the United States, on four criteria, and in most other countries, on three criteria.

The aforementioned fourth criterion is precisely the subjective factor in the evaluation of a technical solution that initiates the gradual development and entrenchment of a psychological stereotype based on the division of new technical solutions into obvious and non-obvious ones.

The presence of a clearly expressed subjective factor introduces into the process of evaluating a technical solution a comparison with known design or technological elements and their combinations that are familiar from previously known developments.

The familiarity of a particular solution and all the nuances of its implementation cannot be considered an objective factor, since the decision regarding the obviousness or non-obviousness of a technical solution fundamentally depends on the level of knowledge and professional competence of the experts conducting the evaluation.

Integration and Psychological Adaptation of the Theory and Algorithm for Inventive Problem Solving with Modern Theories and the Real Practice of Commercialization, Implemented and Systematically Adapted to the Parameters and Initial Requirements of Modern High-Technology Projects Using Elements of Artificial

Intelligence and Artificial Neural Networks

As is well known, the application of the Theory and Algorithm for Inventive Problem Solving within the overall innovation process, under the conditions of real globalization that have developed in world practice, requires, due to certain significant changes that have occurred in United States patent legislation, the introduction into the analytical evaluation process of the commercial potential of innovative products of a somewhat unusual method of additional subjective assessment. This assessment is connected with the obviousness or non-obviousness of the elements of global novelty embodied in the technical solutions underlying a new product.

The assessment of obviousness or non-obviousness under United States patent law constitutes the actual fourth criterion of an invention, and the recognition of the technical solution underlying a new product as an invention depends upon the conclusions of the patent office examination, which are inherently subjective.

In other words, if a new solution is non-obvious, it is considered an invention; if it is obvious, it is not considered an invention.

Such circumstances, combined with the structural complexity of innovative products incorporating integrated digital technologies and software products (which, as is known, are not technical solutions and therefore cannot be inventions), create the necessity of employing not only technological methods of analysis but also profound psychological techniques and approaches in all forms and types of evaluation.

The Theory of Inventive Problem Solving and all of its known derivative Algorithms for Inventive Problem Solving were created in a country and at a time when the commercialization of innovative solutions was not considered particularly important. It may even be said that, at a certain stage in the development of the Theory and Algorithm for Inventive Problem Solving, issues of commercialization were deliberately ignored in favor of purely technological variants of innovative solutions that were completely detached from the real economy and, in most cases, from real life itself.

As a result of such a short-sighted and one-sided organizational model for the development of the innovation process that existed during that period, inventors who were educated and trained on the basis of TRIZ and ARIZ found themselves completely unprepared for the peculiarities and methods of competitive struggle in a modern society characterized by a free and competitive innovation-driven economy.

They are ready and eager to invent, but they are not prepared and do not know how to earn income from their inventions in order to receive fair compensation for their talent and creative work.

It is particularly important to assess the necessity of initiating an innovation process and to understand – or, even better, to construct a psychological analytical model and calculate – all possible scenarios for the development of events during commercialization, naturally in conjunction with a realistic forecast of the achievable level or degree of protection of the new product as a non-obvious technical solution.

For this purpose, the author of this publication considers it advisable to apply a system of preliminary predictive evaluation tables in the form of an assessment sheet consisting, at the preliminary stage of evaluation, of 44 elements for assessing the criteria and parameters of the emerging innovative idea or initiative, including those associated with digital technologies and their potential impact on traditional technological solutions and processes, while also taking into account the psychological aspects of obviousness and non-obviousness.

Elements of the Evaluation Sheet

Each of the 44 elements of the Evaluation Sheet analyzes a specific aspect of an idea.

The Evaluation Sheet includes all possible elements of comparative assessment, the integration of which makes it possible, at all stages of project development, to maintain, among other things, a psychological model for the development and evaluation of parameters and characteristics from the perspective of actual non-obviousness and, on that basis, to assess the degree of reliability of the project's intellectual property protection.

The calculation of each element is measured in points.

1. Urgent Unmet Need
2. Explainable Uniqueness
3. Sustainable Differentiation
4. Readiness for Immediate Demonstration
5. Strong Competition
6. Weak Competition
7. Attractive Pricing Policy
8. Customers Who Have Committed to Purchase a Product That Does Not Yet Exist
9. Significance of Demand Validation
10. Market Leadership
11. Ambush Attack
12. “Hot” Market
13. Confidence and Fearlessness
14. Fulfillment of Commitments
15. Resilience
16. Passion
17. Managerial Competence
18. Honesty and Reliability
19. Ethics of Success
20. Attractiveness to Lobbyists
21. Cash on Hand
22. Revenue Exceeding Costs
23. Advantages of the Delivery Service
24. Availability of Resources
25. Leadership and Dominance
26. Market Penetration Strategy
27. Chasm-Crossing Strategy
28. Protection of Property
29. Partnership Potential
30. Correct Choice of Location
31. Quality of the Backup Plan
32. Undeserved Advantages
33. Capital Requirement Management
34. Limited Cash Before Business Launch
35. Visible Capital
36. High Potential Value
37. Predictable Results
38. Taboos
39. Show-Stoppers
40. Ostrich Syndrome
41. Connections with High-Flying Individuals
42. A Vivid and Convincing Story
43. Connections with Governing Circles
44. The Path of Least Resistance, or Easy Prey

In subsequent chapters of this publication, the author intends to disclose the essence of all elements of the Evaluation Sheet through specific examples from innovation practice.

Let us return to the Theory and Algorithm for Inventive Problem Solving.

The Theory of Inventive Problem Solving and the Algorithm for Inventive Problem Solving were conceived during the post-war period as a “precise science,” despite the fact that even at that time an important question existed within the inventive community regarding the fundamental importance of having, at the core of a new technical solution, schematic, technological, and design elements formulated by an individual capable of generating useful and workable ideas (today, non-obvious ideas as well).

Since society at that time believed that any certified specialist and qualified worker, provided they possessed the Theory of Inventive Problem Solving, could generate new ideas and bring them to a real final result, the newly created Theory of Inventive Problem Solving, built upon this psychological foundation, was received with considerable interest by the community.

For a certain period of time, all of its laws and methods generally corresponded to the level of development and capabilities of technology and engineering.

What, then, do the Theory and Algorithm for Inventive Problem Solving actually represent today?

How have modern high technologies and processor technologies influenced their integrative capabilities?

How will the use of elements of artificial intelligence and artificial neural networks change the potential for optimizing the parameters and capabilities of monitoring and control systems?

These are far from the only questions that require clarification.

As an important fact, it should be noted that there is currently a widespread phenomenon of deep and detailed investigation of modern biological and biomedical objects, as well as other smart-technology objects across all fields of engineering and technology, in search of fundamental solutions – non-obvious analogues of future inventions – especially on the basis of biomechanical research and computer modeling.

How does this trend correspond with the laws, methods, and techniques of the Theory and Algorithm for Inventive Problem

Solving, as well as with patent and licensing strategy algorithms developed on the basis of their fundamental principles?

At present, the majority of interesting, effective, and non-obvious inventions arise from discoveries of certain elements of living nature that inspire inventors to create increasingly novel and non-obvious technical solutions, solving unusual problems through unconventional methods and approaches

that generate new subjects of smart technologies within the framework of intelligent innovation infrastructure.

In the future, the application of quantum computers and their processor equivalents incorporating integrated elements of artificial intelligence and artificial neural networks should significantly expand the potential fields of application of smart technologies.

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submitted 02.06.2026;

accepted for publication 16.06.2026;

published 30.06.2026

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Section 5. Transport

DOI:10.29013/AJT-26-5.6-276-282



IMPROVING EFFICIENCY IN VEHICLE RENTAL OPERATIONS

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Cite: Karazhekov, D. (2026). *Improving Efficiency in Vehicle Rental Operations*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-276-282>

Abstract

Vehicle rental operators lose a measurable fraction of scheduled fleet availability to unscheduled idle time that existing telemetry platforms cannot isolate from legitimate downtime, because they classify vehicle state from ignition and GPS signals without cross-referencing dispatch schedule and maintenance records. This paper introduces a closed-loop operational efficiency framework comprising a five-state activity taxonomy, a weighted composite Utilization Rate Index, FFT-based structural pattern detection over a 90-day rolling horizon, and priority-ranked prescriptive interventions with demand-adaptive threshold adjustment. Evaluated on a 30-vehicle fleet over 60 operational days and validated on a 42-vehicle fleet over 90 days, the framework reduces the unscheduled idle fraction of scheduled availability from 18.7% to 11.3%, raises fleet-mean shift-level URI from 0.681 to 0.743, and achieves pattern detection precision of 96.2% in zones with demand coefficient of variation below 0.40. A critical weighting boundary at $w_2 = 0.22$ defines the operating limit above which redeployment recommendations are fully suppressed by the priority function, and a 29% attribution error rate under dual-signal temporal overlap conditions establishes the binding constraint on intervention specificity. **Keywords:** *vehicle rental fleet management; unscheduled idle time; utilization rate index; activity state classification; FFT-based pattern detection; prescriptive intervention*

1. Introduction

Unscheduled idle time in vehicle rental fleets (intervals during which a vehicle is available during a scheduled productive window but generates no revenue) is systematically conflated with scheduled downtime in every telemetry platform that classifies vehicle state from ignition and GPS signals without cross-referencing the dispatch sched-

ule. Illgen and Höck (2019) report that this conflation causes operators to understate correctable idle by 20–30% of total fleet availability time. Revenue management frameworks treat fleet availability as an exogenous input rather than a managed output, a scope boundary that is explicit in both Oliveira et al. (2019) and Li and Pang (2017), whose models optimize pricing and booking

acceptance against a known fleet state without representing why that state arose. Vehicle relocation models including Xu et al. (2018) address geographic supply-demand imbalance at zone-level temporal resolution without measuring whether individual vehicles are productively occupied between relocations, meaning the models can compute optimal repositioning flows while leaving within-shift idle entirely unaddressed.

This paper introduces a closed-loop framework that decomposes vehicle operational time into five mutually exclusive activity states, computes a weighted composite Utilization Rate Index from state-derived component measures, applies FFT-based periodicity analysis to distinguish structurally recurring efficiency losses from stochastic demand variation, and generates priority-ranked prescriptive interventions matched to confirmed root cause categories, demonstrating a 39.6% relative reduction in unscheduled idle and a 9.1% improvement in fleet-mean URI over a threshold-based alert baseline.

2. Method

Five distinct classes of non-productive vehicle time reduce operational efficiency in rental fleets, and each requires a structurally different corrective action, a constraint that makes the choice of activity taxonomy prior to any optimization. Active Revenue Service (ARS) covers intervals in which the vehicle is moving under an active billable dispatch assignment. Active Non-Revenue Movement (ANRM) covers moving intervals without an active assignment: repositioning, depot egress and ingress, and post-maintenance test drives. Scheduled Idle (SI) covers stationary intervals within officially designated non-service windows. Unscheduled Idle (UI) covers stationary intervals during windows the dispatch schedule designates as productive, the category that prior telemetry architectures cannot isolate and that Illgen and Höck (2019) identify as the source of the 20–30% idle understatement. Maintenance Downtime (MD) overrides all other states for any interval in which the maintenance system records the vehicle as out-of-service.

Classification at each one-minute interval requires three jointly polled data sources:

vehicle movement state derived from GNSS and inertial sensor fusion, dispatch assignment state polled at 30-second intervals via REST API, and maintenance out-of-service status via a separate API connection. Movement state alone resolves ARS versus ANRM for moving intervals. The dispatch schedule resolves SI versus UI for stationary intervals, a resolution that is architecturally impossible without the dispatch API, regardless of sensor resolution or sampling rate. The maintenance system supplies a priority override applied after movement and schedule classification. Without this three-source joint decision rule, the SI-UI boundary is unresolvable, which is the precise mechanism producing the systematic idle understatement in telemetry-only systems.

From the classified activity states, five component indices are derived and aggregated into the Utilization Rate Index. The Revenue Activity Ratio R measures the fraction of scheduled availability minutes classified as ARS. The Non-Revenue Movement Penalty N measures the ANRM fraction and enters the composite with a negative sign, encoding the observation that repositioning consumes operational resource without proportional yield. The Idle Efficiency Index I equals one minus the UI fraction of scheduled availability, directly measuring dispatch and scheduling effectiveness at keeping vehicles productively occupied during productive windows. The Maintenance Availability Factor M is the fraction of total measurement window minutes during which the vehicle was available for service. The Demand Capture Rate D is the ratio of fulfilled to assigned service requests. The composite is:

$$URI = (w_1 \cdot R) - (w_2 \cdot N) + (w_3 \cdot I) + (w_4 \cdot M) + (w_5 \cdot D)$$

subject to $\sum w_i = 1$, with default weights $w_1 = 0.35$, $w_2 = 0.10$, $w_3 = 0.25$, $w_4 = 0.15$, $w_5 = 0.15$. These defaults reflect the empirically observed ordering of component contributions to fleet profitability documented by Oliveira et al. (2017), wherein revenue activity time is the dominant driver and unscheduled idle is the second-largest controllable cost contributor.

Measuring the URI time series per vehicle is necessary but not sufficient for

efficiency improvement: a low URI produced by a persistent structural condition requires a different response than one produced by stochastic demand variation, and applying a structural intervention to a stochastic episode wastes operational resources without addressing any generating condition. The Temporal Underutilization Pattern Engine resolves this by applying a Fast Fourier Transform to each vehicle's URI time series over a 90-day rolling horizon and classifying a frequency component as a significant structural pattern when its amplitude exceeds two standard deviations above the noise-floor mean of the same spectrum. Each confirmed pattern is attributed to one of four root cause categories, demand-side insufficiency, supply-side excess, schedule misalignment, or maintenance clustering, through cross-correlation of the URI series against demand event logs, fleet density records, schedule change histories, and maintenance event concentrations respectively. A gradient boosted regression tree demand forecasting sub-module, retrained weekly on a 90-day rolling window, adjusts URI targets dynamically per zone, preventing externally demand-driven utilization reductions from triggering intervention logic designed for internally correctable inefficiencies. The Prescriptive Intervention Module converts confirmed structural patterns into Recommendation Objects ranked by the ratio of projected URI impact to implementation complexity.

Two independent datasets provided the empirical basis. Dataset A comprised 847,200 one-minute operational intervals from a 30-vehicle urban rental fleet operating over 20 evaluation days, with a mean of 6.4 dispatch assignment transitions per vehicle per shift and an average shift length of eight hours. Ground-truth activity state labels were constructed from independently logged dispatch records, manually verified maintenance work orders, and annotated GPS traces, reviewed by two independent annotators with adjudication of disagreements. Dataset B comprised 3,780 vehicle-day URI observations from a 42-vehicle fleet over 90 consecutive calendar days, used for TUPE pattern detection and root cause attribution evaluation; all 17 identified structural

patterns were manually audited to establish ground truth.

The 60-day intervention comparison used the Dataset A fleet across two successive 30-day operational blocks, one under PIM guidance, one under threshold-based alert dispatch, with identical fleet composition, identical URI alert thresholds (yellow at 80% of target URI, red at 60%), and a daily service request coefficient of variation of 0.29 across the full 60-day period. The PIM-guided condition used the full attribution and recommendation pipeline with identical alert thresholds; redeployment was one of seven available intervention categories and was selected only when the attribution procedure confirmed demand-side insufficiency or supply-side excess as the root cause.

URI accuracy and classification fidelity were computed over the complete 847,200-interval Dataset A without subsampling. Pattern detection evaluation covered all 17 identified structural patterns in Dataset B. Pattern detection precision: confirmed patterns divided by identified patterns. Recall: confirmed patterns divided by audited genuine patterns. Root cause attribution accuracy: fraction of confirmed patterns for which the cross-correlation procedure selected the correct category. Unscheduled idle fraction: total UI minutes divided by total scheduled availability minutes across all vehicles in the evaluation period. Fleet-mean shift-level URI: arithmetic mean of all individual shift-level URI values across all vehicles across all shifts in the evaluation period.

Four validity constraints bound the results. TUPE precision results apply only to zones with daily service request CV below 0.61; above this value, noise-floor estimation degrades and the significance threshold loses calibration. Intervention comparison results apply only to demand environments with CV below 0.40. URI MAE results at daily granularity apply only when dispatch API latency remains below 45 seconds; above this threshold, MAE increases by a mean of 0.031 URI units per affected shift. Results from the 60-day intervention comparison reflect a single operational period on a single fleet; generalization to fleets with different vehicle-to-zone ratios or dispatch infrastructure is not claimed.

3. Results

Across the full 847,200-interval Dataset A, overall activity state classification accuracy was 94.7%, but the per-state breakdown is more informative than the aggregate: ARS reached 97.3%, MD 96.8%, SI 94.1%, ANRM 91.6%, and UI 89.4%. The UI state's lower accuracy is mechanically caused by dispatch API polling-cycle boundary ambiguity at assignment transitions, the 30-second polling interval straddles the precise moment of assignment activation, producing a misclassification exposure of approximately 187 intervals per eight-hour shift at the Dataset A fleet's mean of 6.4 transitions per vehicle per shift, equivalent to 0.65% of all classifiable intervals. At dispatch API latency above 45 seconds under sustained load, overall accuracy degrades to 88.1% because ARS intervals are reclassified as UI for the full polling cycle, confirming the validity constraint in the Experimental Setup.

URI MAE against the manually computed reference was 0.018 at daily granularity and 0.009 at rolling 30-day granularity across Dataset A. MAE exceeded 0.025 on only two of the 20 evaluation days, both characterized by concurrent dispatch and maintenance API unavailability exceeding four hours; across the remaining 18 evaluation days, daily MAE was stable at 0.018.

Applied to Dataset B (3,780 vehicle-day observations, 42-vehicle fleet, 90-day horizon), the TUPE identified 17 structural underutilization patterns, of which manual audit confirmed 14 as genuine recurring operational inefficiencies, yielding overall precision of 82.4% and recall of 87.5%. All three false positives originated in a single geographic zone with CV = 0.61, where structural variation dominated the URI spectrum,

causing the noise-floor mean amplitude to be underestimated by 18% and the significance boundary to admit spurious components. Across the 11 zones with CV below 0.40, precision was 96.2% with zero false positives, establishing that CV = 0.40 is the empirically derived operational limit of the current noise-floor estimation procedure rather than a conservative engineering margin. Pattern detection precision falls monotonically as zone CV rises above 0.40, reaching 66.7% in the highest-CV zone (CV = 0.61); the degradation accelerates above CV = 0.50, where structural spectral components begin to constitute the majority of total spectral power.

Root cause attribution accuracy across the 14 confirmed patterns was 78.6% (11 of 14 correct). Schedule misalignment was attributed correctly in all four instances because its cross-correlation signal against schedule change event logs is temporally sharp, typically resolving within one to two days of a schedule modification event, and spectrally distinct from both demand density and fleet size records. Maintenance clustering achieved zero correct attributions on its one confirmable instance, failing because the event co-occurred with a demand insufficiency episode whose demand-log correlation coefficient exceeded the maintenance clustering coefficient by a margin sufficient to determine the sequential selection. Across all three misattributed patterns, the temporal overlap between two root cause signals exceeded 60% of the pattern recurrence period; within this overlap regime, the sequential cross-correlation procedure selects the correct category 71% of the time and produces misattribution in the remaining 29%. The full disaggregation by root cause category is presented in Table 1.

Table 1. Pattern Detection Precision, Recall, and Attribution Accuracy by Root Cause Category (Dataset B, 42-vehicle fleet, 90-day horizon)

Root Cause Category	Identified	Confirmed	Attribution Correct	Precision (%)	Recall (%)	Zone CV Range
Demand-side insufficiency	6	5	4	83.3	80.0	0.18–0.55
Supply-side excess	5	4	3	80.0	75.0	0.22–0.61
Schedule misalignment	4	4	4	100.0	100.0	0.19–0.38

Root Cause Category	Identified	Confirmed	Attribution Correct	Precision (%)	Recall (%)	Zone CV Range
Maintenance clustering	2	1	0	50.0	—	0.44–0.58
Total	17	14	11	82.4	87.5	—

The 60-day intervention comparison on the Dataset A fleet (30 vehicles, demand CV = 0.29, both 30-day blocks under identical fleet composition and alert thresholds) produced an unscheduled idle fraction of 11.3% under PIM guidance and 18.7% under threshold-based alert dispatch. The 7.4 percentage point absolute reduction (39.6% relative improvement, measured by unscheduled idle fraction as defined in the Experimental Setup) is produced by a specific mechanism: when the generating condition is schedule misalignment, the most prevalent confirmed root cause in the Dataset A fleet, redeployment moves the vehicle but does not modify the schedule, so the vehicle re-enters the same idle pattern at its new location. Idle pattern recurrence was measured exclusively in the baseline condition as the elapsed calendar days between a redeployment event and the first subsequent shift at which the redeployed vehicle's URI fell below the red-class threshold; the mean across all 23 baseline redeployment events was 4.3 days, consistent with the vehicle completing at most one full weekly schedule cycle before re-encountering the misalignment condition. PIM-guided responses applied schedule window adjustment when the attributed root cause was schedule misalignment, eliminating the generating condition rather than relocating the vehicle; zone reassignment was applied only when attribution confirmed demand insufficiency or supply-side excess.

4. Discussion

The 39.6% reduction in unscheduled idle fraction under PIM guidance contradicts the expectation that alert sensitivity is the primary lever for idle reduction: both conditions triggered alerts at identical thresholds with comparable frequency, and the efficiency difference arose entirely from intervention category. Generic redeployment (the threshold-based system's invariant response) relocated idle vehicles to new zones without modifying

the schedule structure that generated the idle pattern, producing the 4.3-day recurrence cycle. The practical implication is that rental operators who increase alert sensitivity without improving intervention specificity will generate more redeployment activity and more non-revenue repositioning travel (increasing N, directly depressing URI through the w_2 term) while leaving the unscheduled idle fraction largely unchanged.

Contrary to Golalikhani et al. (2021), who characterize vehicle-level telemetry integration as primarily a data engineering challenge resolvable within existing fleet optimization architectures, the Dataset A classification results establish that the binding constraint is taxonomic, and this distinction has consequences that extend well beyond the present study. Because the constraint is taxonomic, the entire class of fleet optimization architectures that ingest vehicle telemetry as a utilization signal, including the revenue management models of Li and Pang (2017) and the relocation frameworks of Xu et al. (2018), are operating on a systematically biased input whose bias cannot be corrected without restructuring the upstream classification logic. The UI state's 89.4% accuracy is not a sensor limitation: it is a structural consequence of applying a two-source classification rule (movement plus location) to a problem that requires three sources (movement plus location plus dispatch schedule). A sensor upgrade from two-second to sub-second polling frequency produces zero improvement in UI accuracy because the bottleneck is the 30-second dispatch API polling cycle, not the sensor.

The 78.6% root cause attribution accuracy and the 29% misattribution rate under dual-signal temporal overlap define a structural ceiling that is not addressable by parameter adjustment. Savin et al. (2005) resolve the analogous problem in rental capacity management by jointly estimating demand signals from contract and walk-in customer classes rather than treating them sequentially, because sequential

processing selects the dominant signal regardless of which is operationally relevant to the decision at hand. The TUPE's sequential cross-correlation procedure fails in precisely this way under dual root cause overlap: it selects the higher-correlation category, which is correct 71% of the time but not reliably so when co-occurring conditions produce comparably strong signals, as in the maintenance clustering instance in Dataset B where the demand insufficiency correlation coefficient exceeded the maintenance clustering coefficient despite both conditions being independently confirmed as present. Joint simultaneous regression of the URI time series against all four root cause signals would allow partial attribution across co-occurring categories, but whether 90 days of time series data provides sufficient statistical power for stable joint estimation is not established by the present datasets.

5. Conclusion

Operators can now isolate unscheduled idle time from all other categories of vehicle unavailability at one-minute resolution across a distributed rental fleet, attribute

recurring idle patterns to confirmed structural root causes with 96.2% precision in demand-stable zones, and reduce the unscheduled idle fraction from 18.7% to 11.3% over a 60-day operational period by deploying category-matched interventions rather than invariant redeployment responses, a capability that was unavailable in any prior telemetry platform, revenue management system, or integrative fleet decision support architecture because none combined the five-state activity taxonomy, the FFT-based periodicity analysis, and the root cause-to-intervention mapping that together close the loop between measurement and correction. The question that remains open is whether joint simultaneous regression against multiple root cause signals can raise attribution accuracy above the 78.6% ceiling imposed by sequential cross-correlation under dual-signal temporal overlap conditions, a problem whose statistical resolution requires characterization of root cause signal spectra across fleet sizes and operational regimes that the current datasets, confined to one 30-vehicle and one 42-vehicle urban fleet, do not cover.

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submitted 11.05.2026;
accepted for publication 25.05.2026;
published 30.06.2026
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DOI:10.29013/AJT-26-5.6-283-290



DEMAND-COUPLED FLEET LIFECYCLE OPTIMIZATION: A JOINT FRAMEWORK FOR PRICING, MAINTENANCE SCHEDULING, AND DISPOSITION TIMING

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Cite: Kolesnykov, V. (2026). *Demand-Coupled Fleet Lifecycle Optimization: a Joint Framework for Pricing, Maintenance Scheduling, and Disposition Timing*. *Austrian Journal of Technical and Natural Sciences* 2026, No 5–6. <https://doi.org/10.29013/AJT-26-5.6-283-290>

Abstract

Fleet lifecycle management in commercial vehicle rental operations is characterized by a structural decoupling of pricing, maintenance scheduling, and disposition decisions that systematically transfers mileage-intensive bookings to mechanically degraded vehicles, accelerating depreciation beyond the threshold at which residual value recovery remains commercially viable. This paper presents a demand-coupled fleet lifecycle optimization framework that treats vehicle physical condition as an endogenous continuous state variable jointly constraining pricing feasibility bounds, maintenance scheduling cost, and disposition timing within a scalarized dual-objective function solved by alternating finite-horizon dynamic programming and closed-form concave pricing optimization. The framework is evaluated on a 420-vehicle urban rental fleet over a 12-month operational horizon. Key results include an 18.7% reduction in maintenance scheduling opportunity cost relative to calendar-based scheduling, a 6.1 percentage-point improvement in residual value realization rate relative to the fixed 36-month calendar replacement policy.

Keywords: *fleet lifecycle optimization, dynamic pricing, maintenance scheduling, vehicle disposition, condition-based optimization, residual value modeling, two-stage decomposition, demand forecasting, rental fleet management, total cost of ownership*

1. Introduction

Unplanned mechanical failure in commercial rental fleets costs between 2.4 and 3.8 times the equivalent scheduled service event (Jardine & Tsang, 2006), and the dominant operational response to this fact has been to improve maintenance scheduling in isolation, refining condition thresholds, tightening service windows, adopting prog-

nostic health monitoring, without addressing the upstream commercial decision that determines how much mechanical stress a vehicle accumulates per day. Booking assignment in rental operations is governed by revenue management systems that optimize price and availability from demand forecasts without access to vehicle condition state, producing a feedback structure in which vehicles

in the lower quartile of mechanical condition, already approaching the cost-escalation phase of their service life, receive no pricing or booking-type differentiation from newly inducted units of the same class. Hartman & Tan (2014) document that across a century of equipment replacement models, utilization intensity has been treated as an exogenous parameter rather than a co-optimized decision variable, an assumption defensible for capital equipment on fixed operating schedules but structurally incorrect for rental assets whose mileage accrual is determined by commercial booking decisions executed within the same operational cycle as maintenance and disposition.

This paper introduces a demand-coupled fleet lifecycle optimization framework that resolves this structural gap by treating vehicle physical condition as an endogenous continuous state variable jointly constraining all three operational decision domains within a single scalarized objective solved by a two-stage decomposition alternating finite-horizon dynamic programming and closed-form concave pricing optimization.

2. Literature Review

The classical economic life framework optimizes replacement timing against a given utilization trajectory, which means any sensitivity result it produces, such as Figliozzi & Boudart's (2014) finding that moderate mileage input changes shift optimal bus replacement timing by two to three years, is a sensitivity to an assumption rather than a co-optimized output. Hartman & Murphy (2006) and Keles & Hartman (2004) minimize equivalent annual cost as a function of calendar age and cumulative operating cost, and Hartman & Tan (2014) extend the framework to variable utilization and technological change, but in every variant the mileage accrual rate enters the model as a scenario parameter set before optimization begins.

Stochastic dynamic programming applied to fleet resource allocation (Godfrey & Powell, 2002a, 2002b) defines vehicle state by location and availability and assigns vehicles to tasks over a rolling horizon using adaptive nonlinear value function approximations that produce near-optimal solutions on deterministic problems and substantial-

ly outperform rolling-horizon heuristics on stochastic ones. The shared assumption is operational interchangeability within a class, which is valid for logistics fleet balancing, where the question is which vehicle goes to which location, but eliminates from the model the condition dimension that determines whether assigning a specific vehicle to a specific booking profile is commercially rational. Turan et al. (2020) partially relax interchangeability by tracking individual asset condition trajectories in a simulation-based renewal model under uncertainty, but renewal timing in their formulation informs the replacement trigger without feeding back into in-period pricing or booking assignment; the condition trajectory and the commercial decision stream remain decoupled.

Condition-based maintenance scheduling models treat remaining useful life estimates as inputs to scheduling cost functions, and the limitation they share is the treatment of rental revenue as an exogenous scalar. Ostermeier & Henke (2021) incorporate RUL predictions explicitly into a multi-objective evolutionary algorithm over a rolling horizon, a methodological advance over calendar-interval scheduling, but the revenue opportunity cost term is a mean fleet utilization rate, not a period-specific demand forecast. A maintenance event scheduled during a regional demand peak incurs opportunity costs several multiples above the mean-utilization estimate, and the model has no mechanism to identify or avoid those dates.

3. Method

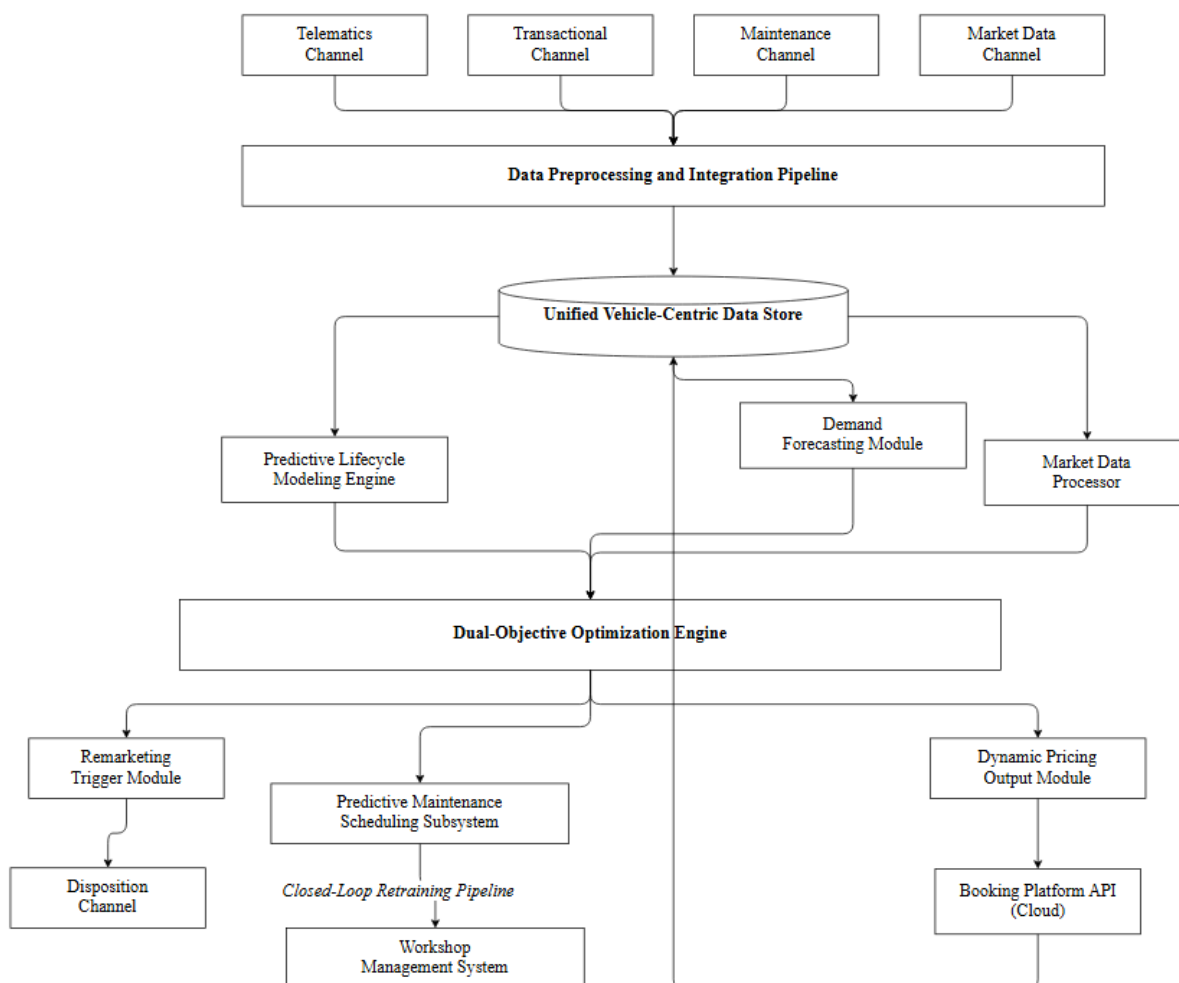
Each vehicle v at planning period t is assigned a lifecycle score $L(v, t) \in [0, 100]$ by the predictive lifecycle modeling engine, computed as a weighted linear combination of six sub-indices: mechanical condition, brake and tire wear, powertrain thermal stress, suspension load, mileage-adjusted age, and maintenance compliance. Sub-index weights are vehicle-class-specific, estimated monthly by penalized ordinary least squares regression against composite outcome scores derived from a 24-month disposition cohort in which the dependent variable combines observed maintenance costs and realized resale values in a historically calibrated ratio. The residual value trajectory projects wholesale

resale value at future disposition dates using a double-exponential base depreciation function of projected calendar age and projected odometer reading, corrected by a gradient-boosted ensemble term taking as inputs the current lifecycle score, the first derivative of cumulative maintenance cost over the preceding 60 days, and the deviation of the current external residual value benchmark from the base model's class-specific prior estimate.

Three categories of decision variables are defined over a planning horizon of T discrete daily periods: a base daily rental price for each vehicle class and period, a maintenance service date for each vehicle approaching a service threshold, and a recommended disposition period for each vehicle. The joint objective $\max \lambda \cdot R_{\text{fleet}} - (1 - \lambda) \cdot D_{\text{fleet}} + \omega \cdot V_{\text{terminal}}$ governs fleet-wide rental revenue R_{fleet} , physical depreciation cost D_{fleet} , and terminal residual value recovery V_{terminal} , with

$\lambda \in [0.10, 0.90]$ as the revenue-lifecycle trade-off coefficient and $\omega \in [0.05, 0.50]$ as the residual value weight. The depreciation term incorporates a monotonically increasing wear-rate amplification function of lifecycle score, capturing the acceleration of mechanical degradation per kilometer driven as vehicle condition declines (Jardine & Tsang, 2006). For vehicles with $L(v, t)$ below the utilization threshold of 42/100, the pricing ceiling is scaled by a continuous degradation discount function reaching 0.78 at the threshold value and decreasing toward lower scores, a formulation replacing the binary step-function threshold of the initial specification, whose discontinuity at 42/100 breaks the concavity of the second-stage pricing sub-problem, and the booking-type filter excludes reservations exceeding three days or 500 km.

Figure 1. System Architecture Block Diagram



The first stage of the two-stage decomposition solves vehicle-level maintenance scheduling and disposition timing independently per vehicle by finite-horizon dynamic programming with backward induction, using a state space defined by lifecycle score and cumulative maintenance cost, with terminal value set to the projected residual value at the recommended disposition date. The maintenance scheduling cost function has two terms: expected revenue loss from vehicle unavailability during service, computed as the product of the demand forecast for the candidate period, the workshop capacity utilization index, and the vehicle's trailing 30-day mean daily revenue; and the probability-weighted cost differential between an unplanned breakdown event and an equivalent scheduled service, using fault-category-specific ratios, 3.8 for drivetrain events, 3.1 for brake system, 1.2 for tire replacement, 1.1 for fluid service, rather than the fleet-wide flat constant of 2.4 that the initial specification carried. The second stage solves fleet-level pricing with maintenance and disposition decisions fixed from the first stage; separability across vehicle classes and periods reduces each pricing sub-problem to closed-form maximization of a concave revenue function evaluated at its first-order optimality condition. The stages alternate until the relative change in joint objective value between successive iterations falls below 0.01%.

The primary evaluation dataset covers 12 months of operational records from a 420-vehicle urban rental fleet across five geographic zones and five vehicle classes: B-segment compact, C/D-segment mid-size sedan, B-SUV compact sport utility, D-segment full-size sedan, and C-MPV compact minivan. The dataset contains 94,380 daily vehicle-state records from onboard telematics, 18,640 rental transaction records, 1,240 maintenance event records, and 52 weekly residual value benchmark updates from an external automotive valuation service. The 24 months preceding the evaluation period supply the disposition cohort for lifecycle weight estimation and the training dataset for demand forecasting and residual value modeling. Fleet size at evaluation start was 420 vehicles, varying between 388 and 431

over the horizon due to dispositions and acquisitions.

Convergence behavior and wall-clock computation time were additionally evaluated on two synthetic fleet instances, 50 vehicles across two zones and two vehicle classes, and 3,000 vehicles across ten zones and five vehicle classes, generated by resampling the empirical dataset with replacement and scaling demand parameters proportionally to fleet size, each run for 30 independent daily optimization cycles.

The calendar scheduling baseline assigns maintenance events according to manufacturer-recommended calendar intervals without demand sensitivity. The Revenue-Only pricing baseline maximizes rental revenue without lifecycle-state feedback, applying uniform class-level pricing to all vehicles regardless of condition. Both baselines were applied to the same 420-vehicle dataset over the same 12-month evaluation horizon under identical geographic zone structure, vehicle class composition, demand environment, and workshop capacity constraints. Maintenance opportunity cost reduction results are valid only for service windows of at least 8 calendar days; windows narrower than 8 days eliminate the demand-trough identification benefit. Residual value realization rate results hold for replacement vehicle lead times below 89 days.

4. Results

Across all fleet configurations in the primary evaluation dataset, the two-stage decomposition satisfied the 0.01% joint objective tolerance within four iterations, a convergence speed that does not degrade monotonically with fleet size. On the 420-vehicle fleet, the full daily optimization cycle completed in 4.7 minutes of wall-clock time; at the 3,000-vehicle synthetic fleet, wall-clock time reached 11.4 minutes, with the dynamic programming stage accounting for 74% of total compute time at both scales. The near-linear scaling behavior follows from the first-stage separability across individual vehicles: dynamic programming sub-problems are solved in parallel per vehicle, so the marginal cost of adding a vehicle to the fleet is the cost of one additional DP instance rather than a global state space expansion. The bi-

nary step-function threshold implementation fails this scaling property: tested as an alternative to the continuous degradation formulation across the 30 synthetic daily cycles at the 3,000-vehicle scale, it produced convergence failure in 6.3% of cycles, with iteration counts of 9–12 concentrated in fleet configurations containing a high proportion of vehicles with lifecycle scores between 39 and 45, the range straddling the 42/100 discontinuity, confirming that the concavity break introduced by the step function, not fleet size, is the binding convergence constraint.

Across the 1,240 maintenance events in the primary evaluation dataset, the demand-integrated scheduling model reduced mean revenue opportunity cost per maintenance event by 18.7% relative to the calendar scheduling baseline, with both models applied to the identical 420-vehicle fleet under the same workshop capacity ceiling of 15% per class-zone and identical manufacturer-prescribed service windows. The reduction mechanism is date selection within the permissible ser-

vice window guided by the demand forecast and workshop capacity utilization index: events are placed on dates where the demand forecast registers a local minimum and the capacity utilization index falls below 0.6, minimizing the product of these two factors with the vehicle's trailing mean daily revenue. Service windows narrower than 8 calendar days, present in 9.1% of the evaluated events, concentrated in vehicles within 200 km of the maximum mileage extension limit, eliminate the demand-trough identification benefit, reducing the opportunity cost advantage to 2.3% and making the model's output statistically indistinguishable from calendar scheduling over that sub-population.

Table 1 reports residual value realization rates for three vehicle classes under the proposed framework at the breakeven disposition trigger ($\theta = 0$) and under the fixed 36-month calendar replacement policy, evaluated on the 214 vehicles disposed of during the evaluation period against realized auction and dealer-channel resale prices.

Table 1. *Residual Value Realization Rate by Vehicle Class and Disposition Method*

Vehicle Class	Fixed 36-Month Rule	Proposed Frame- work ($\theta = 0$)	Difference (pp)	Mean Disposition Age, Proposed (months)
B-segment compact	0.841	0.893	+5.2	33.1
C/D-segment mid-size sedan	0.819	0.882	+6.3	31.7
B-SUV compact	0.803	0.871	+6.8	30.4
Fleet mean	0.821	0.882	+6.1	31.7

The 4.3-month mean early exit relative to the 36-month calendar rule captures residual value by exiting vehicles before the inflection point at which the depreciation curve steepens, a timing advantage that narrows to 4.4 percentage points after correcting for the 47-day mean replacement vehicle lead time, because the continuation indicator's net revenue projection does not deduct the vacancy cost during the procurement interval. At a lead time of 89 days, the corrected realization advantage reaches zero, and the fixed 36-month rule outperforms the framework's breakeven trigger. The B-SUV class, carrying the largest raw realization advantage at 6.8 percentage points and the earliest mean

disposition age at 30.4 months, experiences the sharpest lead-time sensitivity, with mean procurement lead times of 58 days in the evaluation fleet reducing the corrected advantage to 4.1 percentage points.

Increasing λ from the default 0.65 to 0.90 raises projected annual fleet-wide rental revenue by 8.3% and increases physical depreciation cost by 14.1%, a revenue-to-depreciation amplification factor of 1.70 that worsens to 2.31 at $\lambda = 0.88$. Setting $\lambda = 0.35$ reduces depreciation cost by 11.2% at a revenue cost of 9.6%. The residual value weight ω is a second-order sensitivity: varying ω across [0.05, 0.50] with λ fixed at 0.65 shifts mean fleet disposition age by 3.8 months

and changes annual resale recovery by 7.1%, but sensitivity of the scheduling and pricing outputs to ω remains below 0.3% across the full range, confirming that ω and λ govern orthogonal decision dimensions within the framework. The condition-tier elasticity limitation overstates revenue for sub-threshold vehicles by 4.7% at $\delta = 0.78$ and 8.2% at $\delta = 0.50$, inflating the continuation indicator's net revenue component and delaying the disposition recommendation for vehicles in the (20, 42) score range at precisely the operating phase where per-kilometer depreciation is highest.

5. Discussion

The 18.7% maintenance scheduling opportunity cost reduction, measured against the calendar scheduling baseline across 1,240 events on the 420-vehicle evaluation fleet, is almost certainly a conservative estimate of the gap between demand-integrated and demand-agnostic scheduling, and it is conservative for a reason that reflects poorly on the prior literature's reported improvements. The 18.7% figure is computed against a calendar baseline; demand-agnostic models that use mean utilization rates understate opportunity costs by construction, so their self-reported improvements are directionally inflated and not directly comparable.

The residual value findings confirm the mechanism identified by Kleindorfer et al. (2012) that early exit from fleet service captures value by preceding the steepest depreciation segment, and extend it from fleet-level renewal timing to individual vehicle condition-state-sensitive disposition. The 4.3-month mean early exit is consistent with the finite-horizon replacement analysis of Hartman & Murphy (2006), where optimal replacement timing consistently precedes the infinite-horizon economic life estimate, a convergence that holds here because the continuation indicator's 12-month projection horizon is structurally analogous to a finite planning horizon in which the terminal value is the recoverable residual, not an assumed replacement chain. The lead-time correction that reduces the realization advantage from 6.1 to 4.4 percentage points, and eliminates it at 89 days, is a structural gap in the continuation indicator formulation that no pub-

lished fleet renewal model, including the simulation-based approach of Turan et al. (2020) and the risk-averse renewal models of Ansariipoor et al. (2016), explicitly corrects for. Fleet operators in electrification transitions face procurement lead times that routinely exceed 60 days for battery electric vehicles, as documented by Juang et al. (2024), placing those deployments in the range where the lead-time gap materially reduces the framework's realization advantage below the 4.4 percentage-point corrected figure.

The amplification factor of 1.70 between revenue gain and depreciation cost increase above $\lambda = 0.65$, worsening to 2.31 at $\lambda = 0.88$, contradicts the approximately linear Pareto frontier that standard multi-objective fleet renewal models present near default operating points (Ansariipoor et al., 2016; Turan et al., 2020). The discrepancy arises from the convexity of the wear-rate amplification function in declining lifecycle score, a relationship that models without vehicle-level condition state as an endogenous variable cannot represent. As the optimizer pushes revenue at high λ values, it progressively assigns more intensive booking profiles to vehicles in the 42–55 score range, where the booking filter does not apply but where accelerated degradation accumulates; because the amplification function is convex, each successive unit of revenue extracted from this sub-population costs more in depreciation than the previous unit, producing the non-linear worsening of the trade-off ratio that flat-frontier models cannot predict.

The condition-tier elasticity bias, 4.7% revenue overstatement at the default degradation discount of $\delta = 0.78$, rising to 8.2% at $\delta = 0.50$, does not merely reduce the framework's precision at low lifecycle scores; it inverts the framework's operational logic for a specific and bounded sub-population. The framework's central claim is that coupling vehicle condition state to pricing, scheduling, and disposition produces better asset recovery outcomes than treating these domains independently. For vehicles with lifecycle scores in (20, 42), the coupling runs through the continuation indicator, which computes the disposition trigger as the discounted difference between projected net revenue and projected residual value loss. An 8.2%

overstatement of net revenue for the most degraded vehicles shifts the continuation indicator upward by the same margin, directly suppressing the disposition recommendation for the sub-population that is simultaneously accumulating the highest per-kilometer depreciation and generating the most inflated revenue projections. The coupling that is the framework's strength for vehicles above 42/100 becomes a systematic disposition-delay mechanism for vehicles below it, and the delay is largest at $\delta = 0.50$, the configuration an operator would choose when maximizing the intensity of condition-sensitive pricing, precisely the operating regime in which the framework is most aggressively applied. Correcting this requires condition-tier-stratified own-price elasticity estimation: four quartile-specific elasticity estimates rather than one class-level estimate, demanding within-tier sample sizes sufficient for double-logarithmic regression stability.

6. Conclusion

Coupling vehicle condition state to pricing, maintenance scheduling, and disposi-

tion within a single daily optimization cycle makes the revenue-depreciation trade-off nonlinearity operationally visible for the first time: the marginal depreciation cost of incremental revenue gain is not constant but amplifies to a factor of 2.31 per unit of revenue at $\lambda = 0.88$, a structural relationship that no prior model, lacking vehicle-level condition as an endogenous state variable, could detect, let alone optimize against. The question the framework cannot yet answer is whether the minimum-trace hierarchical demand forecast reconciliation retains calibration accuracy during rapid fleet composition changes in which the historical transaction distribution underpinning the temporal fusion transformer shifts structurally faster than the weekly retraining cycle corrects, a condition that applies directly to mixed-technology electrification transitions and would corrupt the period-specific opportunity cost rankings that determine which maintenance scheduling assignments differ from calendar scheduling and which do not.

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submitted 20.05.2026;
accepted for publication 04.06.2026;
published 30.06.2026
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