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DISCOVERY OF TIGIT-TARGETED SMALL MOLECULES AS CANCER THERAPIES

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Abstract

This paper will discuss the results of experiments done on the immune checkpoint TIGIT and the discovery of potential immune checkpoint inhibitors that can bind to it. First, machine learning was used to find potential binding spots on TIGIT and the requirements it needs to bind. Next came the pharmacophore test, a list filled with drugs that are able to bind to TIGIT; 15 were chosen at random. Each drug was then tested using SwissDock, which will find the site that it will best bind with TIGIT. After that, the properties of each drug were analyzed; if it passed Lipinski's Rule, it would go on to the next experiment. Last is the toxicity test, where the toxicity level and traits of each drug were analyzed, and in the end, three drugs were chosen that had the best overall results. The study turned out to be successful, as in the end, 3 drugs were found that have the potential to act as immune checkpoint inhibitors. Although this study was successful, it is not the end of the experiment, as many more drugs can be tested with the same processes.

Keywords: *Translational Medical Sciences, Drug Identification and Testing, Immune Cell and Target, Immune Checkpoint, TIGIT*

Introduction

In this research, we explored one of the immunity checkpoints called TIGIT that serves as a biomarker for early detection of cancer cells. However, it also stops the body's immune system from attacking the cancer cells. The goal of this project is to develop an immune checkpoint inhibitor that can prevent the TIGIT immunity checkpoint from binding to the cancer cell and allow the body's immune system to target and attack the cancer cells before they spread. Currently, there are existing inhibitors for a few other checkpoints, which have been extremely useful, but none have yet been discovered for TIGIT.

In today's world, many people are affected by cancer, and it is one of the leading causes of death worldwide. Statistics have shown that around 1 in 4 people worldwide have cancer, and 1 in 10 will die of cancer (Roy & Saikia, 2016). This shows how much impact cancer has on the lives of people worldwide.

Chemotherapy and radiotherapy have been the main ways of treating cancer (Cao et all, 2013). Chemotherapy involves treatments where drugs contain chemicals that can kill fast-growing cells, such as cancer cells, in the body. Radiotherapy involves using beams of high doses that can slow the growth of cancer cells by damaging their DNA to stop them from dividing (Sridhar & Symonds, 2009; McEntee 1995).

There are many different types of immune checkpoints, all acting as biomarkers that can be used for early detection of cancer cells in the body (Topalian et all, 2016). However, as stated earlier, these checkpoints actually stop the body from attacking these cancer cells and allow them to grow into tumors. To prevent this from happening, a checkpoint would need the presence of an inhibitor to allow the body's immune system to attack the cancer cells (Gubser et all, 2022).

Immune checkpoint inhibitors are proteins that can bind to the immune checkpoints and prevent them from stopping the body's immune system from attacking the cancer cells (Li et all, n.d.). Since the discovery of inhibitors for other checkpoints, there has been a massive improvement in treatment for cancer (Jenkins et all, 2018). However, none has yet been discovered for TIGIT.

The procedure involving immune checkpoint inhibitors is immunotherapy. Ever since, immune checkpoint inhibitors have been a massive success in advancements in cancer treatments (Cai et all, 2023), immunotherapy has been a standard option in treatment (Zhang & Zhang, 2020; Farkona, 2016).

The immunity checkpoint that would be focused on in this experiment is TIGIT, also known as T-cell immunoreceptors. Like all immunity checkpoints, TIGIT prevents the body from attacking cancer cells (Ge et all, 2021). Currently, no inhibitors have been discovered for it yet. This makes the goal of this experiment to discover at least one protein that can act as an inhibitor for TIGIT (Chauvin & Zarour, 2020).

Methods

2.1. Analysis of binding sites in TIGIT

2.1.1. ProteinPlus

By using the code for TIGIT, 5v52, ProteinPlus was able to create a replica of TIGIT, which is used as a base model for the experiment. Then, by enabling DoGSiteScorer, which would find every possible binding spot, it gave me a list of pockets with information on their volume, surface area, and drug score. This information would help determine which protein can best bind with TIGIT in certain pockets.

2.1.2. FT site

After loading up the FT site, I input the code for TIGIT, 5v52, along with some other information like email and job name. Afterward, it will start generating the model. After a while, it would generate the model along with binding sites that rely on energy levels. Each different binding site is labeled with a different color, similar to ProteinPlus.

2.1.3. PrankWeb

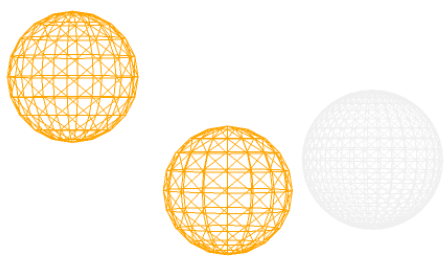
After loading up PrankWeb, I input the code for TIGIT, 5v52. Previously, ProteinPlus used shape and size to determine binding sites, and the FT site uses energy level. PrankWeb determines sites based on both. After the model loads up, I changed the polymer coloring from only white to conservation, as it gives a slightly better visual model. On the right, it will show information on sites, pockets that the algorithm detects.

2.2 Potential Inhibitors test for TIGIT

2.2.1 Pharmacophore

For the Pharmacophore model, I used the Pharmit website, and by entering the TIGIT code, 5v52, it generated a model of TIGIT. The Ligand and Receptors were then turned off, as the only thing needed visible were the Hydrogen Donors and Acceptors. (Figure 1) Then, by clicking "Search MolPort", it will search for every drug that can have the shape needed to connect to both the donor and acceptors, 15 of which will be used in the experiment.

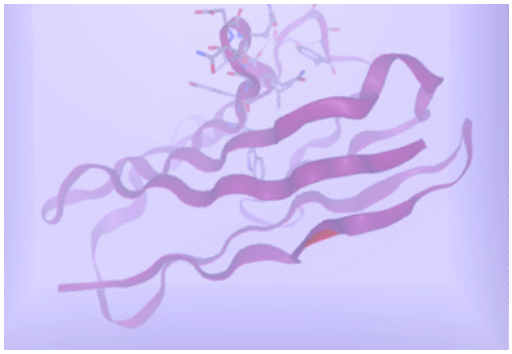
Figure 1. *Picture of 2 Hydrogen Acceptors, orange, and 1 Hydrogen Donor, white. Ligands and Receptors also turned off*



2.2.2 Drug Test (SwissDock)

For the drug Test with SwissDock, I first ran each drug on the drug shop website to find its corresponding SMILES code, which was entered as the ligand. I then set TIGIT, using code 5v52, as the target and selected the chain to keep, T-cell immunoreceptor with Ig and ITIM domains for all tests, and no heteroatoms to keep. I then used the coordinates below for the area of the search box, making sure it covers the whole receptor. (Figure 2) After this, I checked the parameter, which would give an estimate of how long it would take, around a minute for every drug in this experiment. After everything was finished, the start docking button was hit, and the testing began.

Figure 2. *Image of box for Molport-019–897–498, coordinates are Center: –5, 6, –38; Box Size: 44, 25, 30. Same ones will be used for all other drugs*



2.2.3 Drug Test P. 2 (SwissADME)

First, I loaded up the SwissADME app, which requires the SMILES code for each drug being tested. The requirements that each drug has to pass are Lipinski's Rule, stating that each molecule can have no more than 5 hydrogen donors, 10 hydrogen acceptors, a mass of less than 500 daltons, and a calculated LogP of no more than 5. If it meets all the requirements, it can move on to the next experiment.

2.2.4 Toxicity Test

After loading the Pro-Tox website, I selected the toxicity prediction. For the toxicity test, I first got the SMILE code for each drug that passed Lipinski's Rule, all except for Molport-001–947–650. After loading the drug, all of the toxicity models are selected so that it can predict the toxicity of every effect the drug might have on the body.

Results and Discussion

3.1. Analysis of binding sites in TIGIT

3.1.1. ProteinPlus

After generating a list of possible pockets using DoGSiteScorer, there were 19 total, each corresponding to its own color, as shown in the generated result. (Figure 3) Each of the pockets has a volume of around 100A3–500A3, a surface area of around 200A2–700A2, and a drug score of less than one. (Table 1)

Figure 3. *Model result of predicted binding sites in TIGIT using the geometric method ProteinPlus. Colored spheres represent the binding sites*

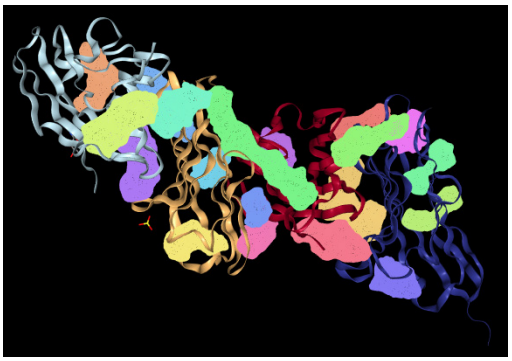


Table 1. *Summary of the predicted binding sites in TIGIT using Protein Plus*

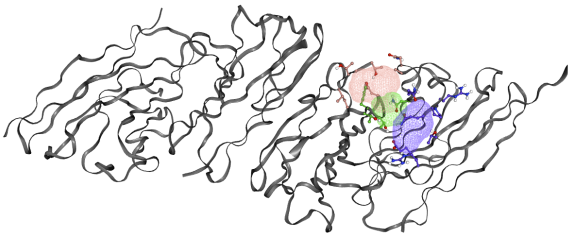
Name	Volume (A^3)	Surface Area (A^2)	Drug Score
P_0	508.4	721.95	0.72
P_1	457.47	641.42	0.69
P_2	417.89	581.35	0.8
P_3	363.44	642.32	0.65
P_4	299.83	552.72	0.62

Name	Volume (A^3)	Surface Area (A^2)	Drug Score
P_5	262.16	388.88	0.62
P_6	240.8	348.85	0.59
P_7	224.01	461.21	0.35
P_8	222.97	388.97	0.31
P_9	215.62	394.09	0.35
P_10	207.04	512.96	0.39
P_11	178.05	307.53	0.36
P_12	164.32	311.82	0.33
P_13	158.21	225.41	0.37
P_14	151.63	262.3	0.29
P_15	151.16	367.85	0.51
P_16	118.92	384.76	0.41
P_17	105.0	251.97	0.21
P_18	102.42	328.18	0.4

3.1.2. FT site

After running the test on the FT site, the result generated showed three different binding sites. This means that there are only three sites on TIGIT that rely on the energy level of the drugs to find, which is significantly less compared to the geometric shape shown earlier. The three sites' location is shown in the results. (Figure 4)

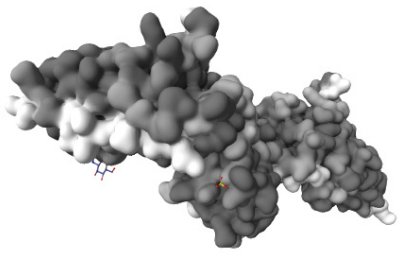
Figure 4. *Model result of potential binding sites generated from FT Sites, three binding sites found are shown in different colors*



3.1.3. PrankWeb

After generating the model (Figure 5), the algorithm suggests that no pockets were found, meaning all of the sites found previously in ProteinPlus and FT sites all relied on either energy level or specific shape, and none relied on both.

Figure 5. *Model result of potential binding sites generated from PrankWeb, no binding sites found as none relied on both shape and energy level*

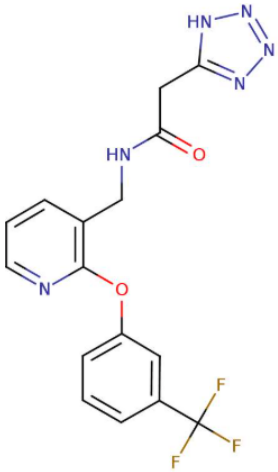
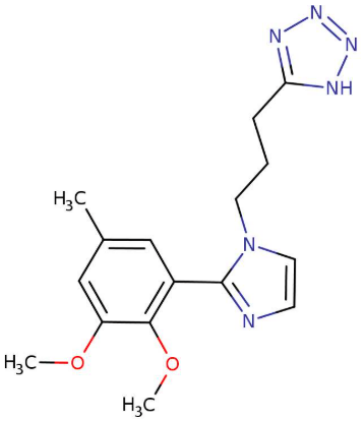
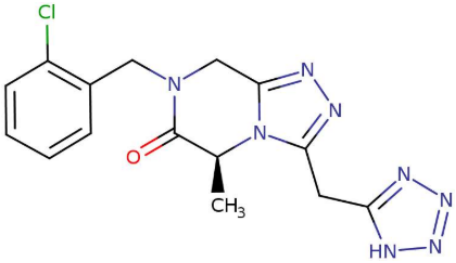
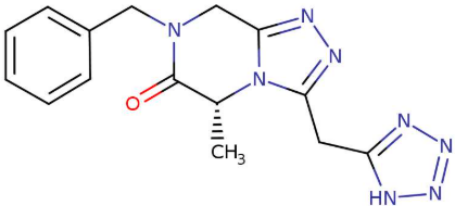
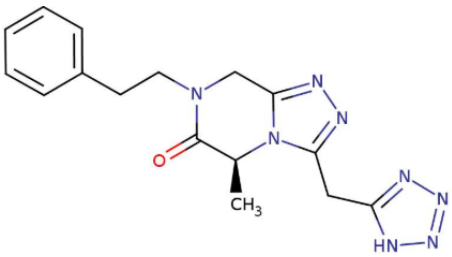


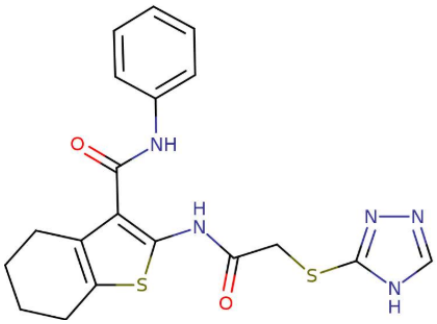
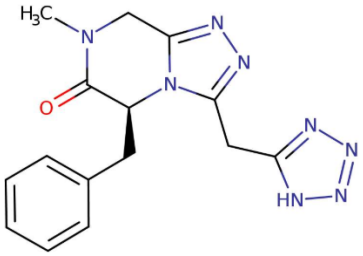
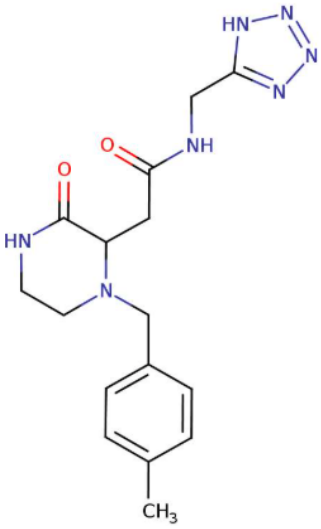
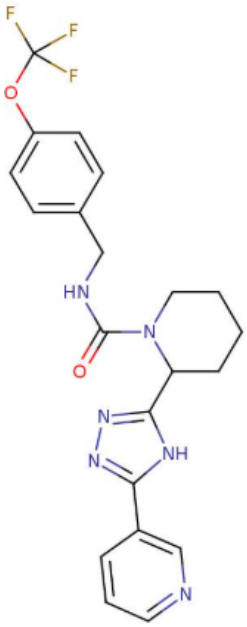
3.2 Analyzing Potential Inhibitors Test for TIGIT

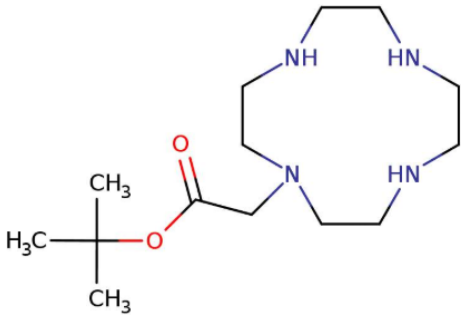
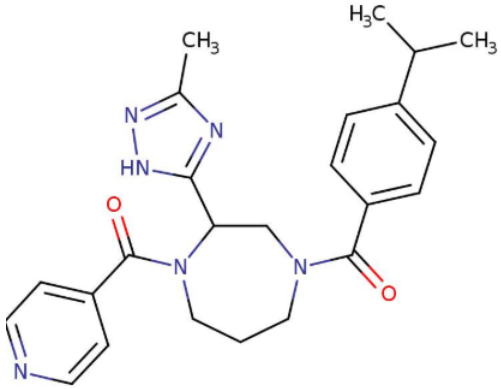
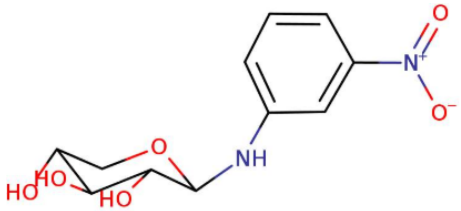
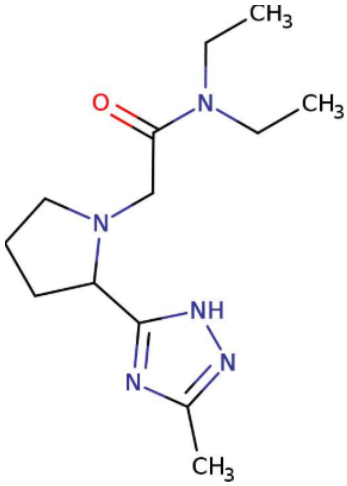
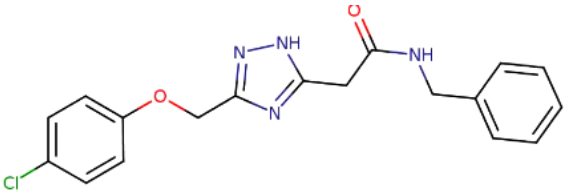
3.2.1 Pharmacophore

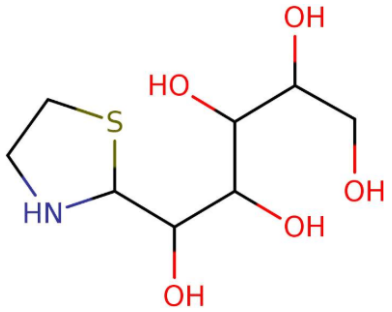
After deselecting the ligands and receptors, making sure two hydrogen acceptors and one donor are present, and searching for drugs, it generated a list with millions of different drugs that can fit the pattern of the acceptors and donors that were shown in Figure 1. In this experiment, 15 of these will be used for the Swiss testing phase. (Table 2) Each of these drugs also has a different RMSD, deviation score, which is how similar the computer simulation is compared to a real-life 3D model; the lower the score, the better.

Table 2. *Information on 15 selected drugs from Pharmacophore hydrogen donor + acceptor pattern*

Name	RMSD	Mass	RBnds	Picture
Mol-port-019–897–498	0.004	378	8	
Mol-port-051–532–927	0.005	328	7	
Mol-port-051–462–100	0.005	359	4	
Mol-port-051–454–708	0.005	324	4	
Mol-port-051–452–917	0.006	338	5	

Name	RMSD	Mass	RBnds	Picture
Mol-port-002–621–450	0.008	414	8	
Mol-port-051–470–239	0.009	324	4	
Mol-port-020–229–987	0.009	343	7	
Mol-port-044–334–503	0.009	446	8	

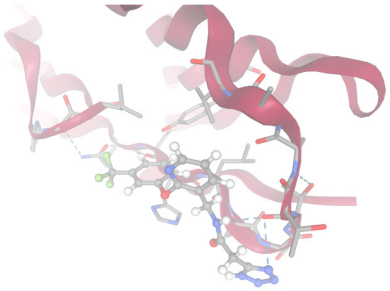
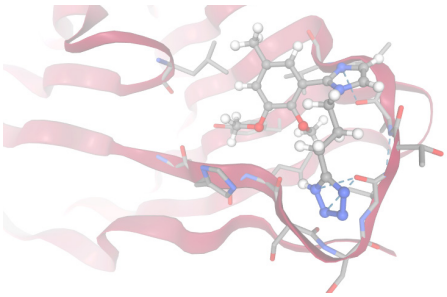
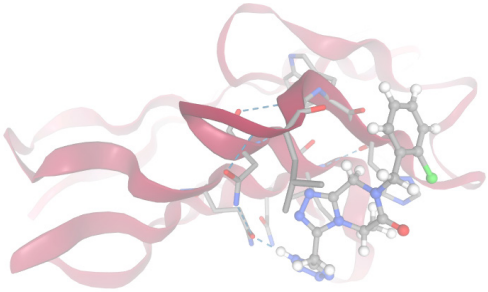
Name	RMSD	Mass	RBnds	Picture
Mol-port-051–517–110	0.009	286	4	
Mol-port-046–059–093	0.010	433	6	
Mol-port-000–814–864	0.010	270	3	
Mol-port-039–048–085	0.011	265	6	
Mol-port-005–953–974	0.011	357	8	

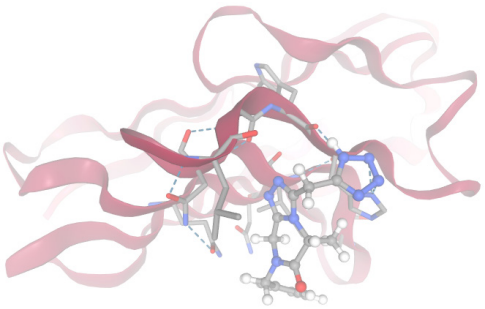
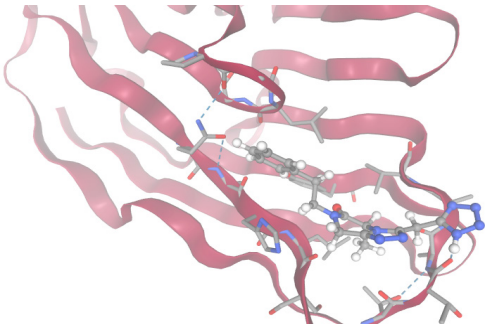
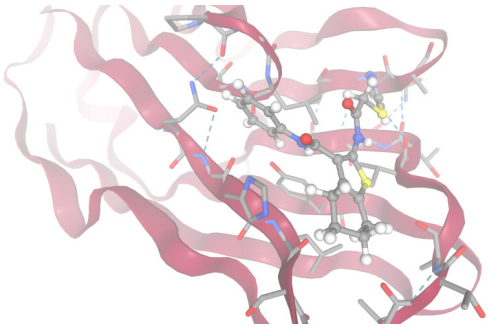
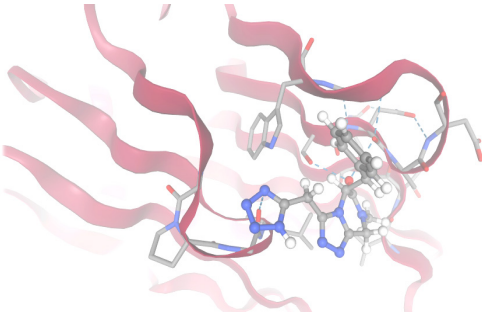
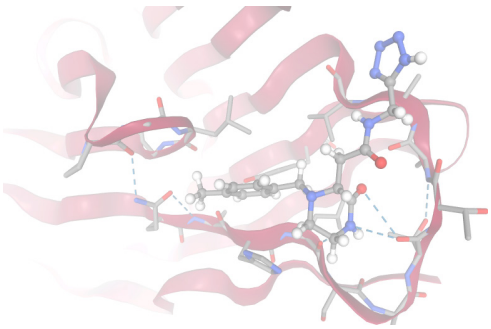
Name	RMSD	Mass	RBnds	Picture
Molport-001–947–650	0.011	239	5	

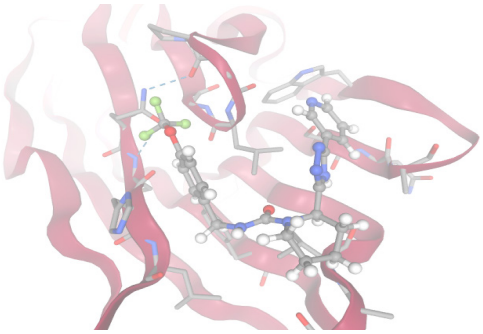
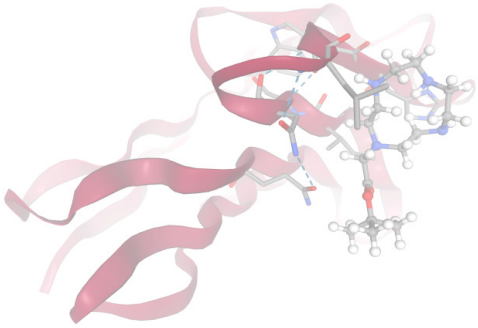
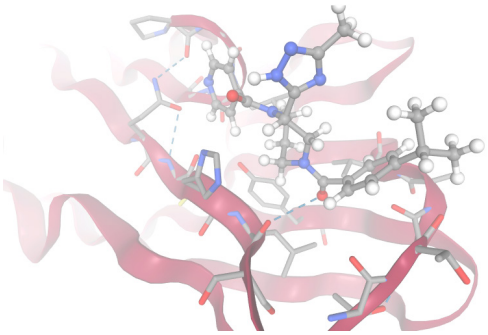
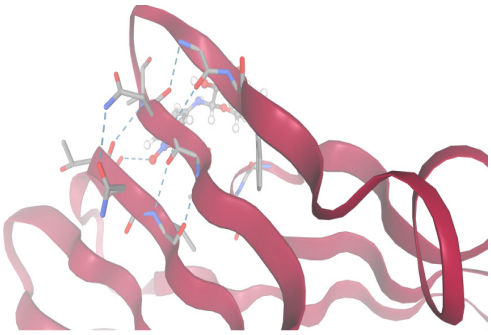
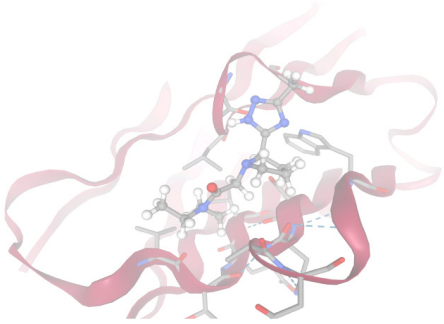
3.2.2 Drug Test (SwissDock)

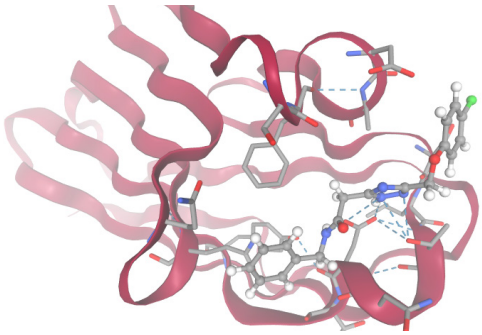
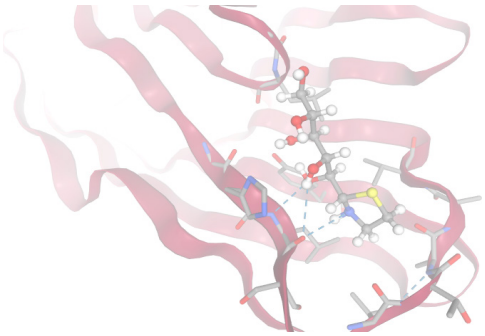
After each drug has finished docking, it generates a list of different sites that it can bond to with TIGIT. Each site is also provided with its SwissParam Score and its AC score. In this experiment, only the site with the lowest SwissParam Score will be used, because the higher the score, the more energy is required for the binding to happen, meaning the lower the level, the reaction will be more spontaneous, happen more easily, and will be used. AC score won't be noted as it isn't necessary. (Table 3) Also, while experimenting, some drugs had to be switched as the SMILES code wouldn't work due to the drugs being more than a single compound, and SwissDock can only take in a single compound.

Table 3. *Information on the 15 drugs' SwissParam score and its best binding location on TIGIT*

Name	SwissParam Score kcal/mol (Lowest)	Binding pose of the compound to TIGIT
Molport-019–897–498	–6.8858	
Molport-051–532–927	–6.7659	
Molport-051–462–100	–6.3235	

Name	SwissParam Score kcal/mol (Lowest)	Binding pose of the compound to TIGIT
Molport-051–454–708	–6.6169	
Molport-051–452–917	–6.7975	
Molport-002–621–450	–6.9804	
Molport-051–470–239	–6.6692	
Molport-020–229–987	–6.5529	

Name	SwissParam Score kcal/mol (Lowest)	Binding pose of the compound to TIGIT
Molport-044–334–503	–7.0876	
Molport-051–517–110	–6.0777	
Molport-046–059–093	–6.6911	
Molport-000–814–864	–5.9198	
Molport-039–048–085	–6.4024	

Name	SwissParam Score kcal/mol (Lowest)	Binding pose of the compound to TIGIT
Molport-005–953–974	–6.8880	
Molport-001–947–650	–5.8708	

3.2.3 Drug Test P. 2 (SwissADME)

After running each drug through SwissADME, the molecular weight, number of hydrogen acceptors and donors, and the CLogP, average LogP score, are noted, as these are the factors required to be checked with Lipinski's Rules. After checking each, the results were that all of the drugs fit the requirements except Molport-001–947–650 (Table 4), which had 6 hydrogen donors, and the limit is 5. Besides this, all other drugs were good for use.

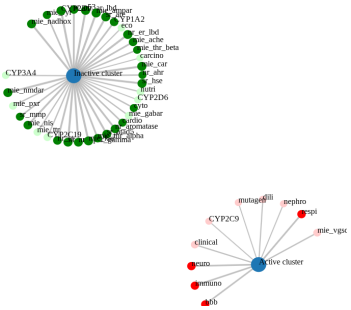
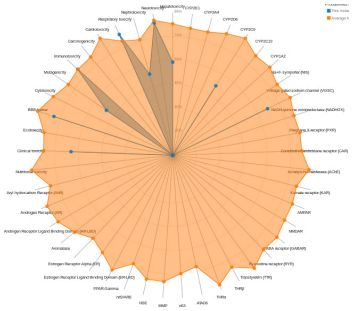
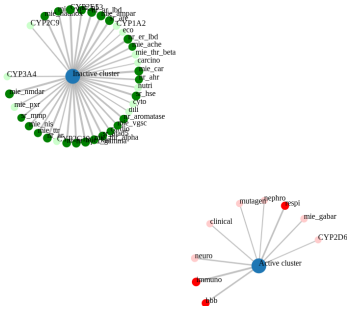
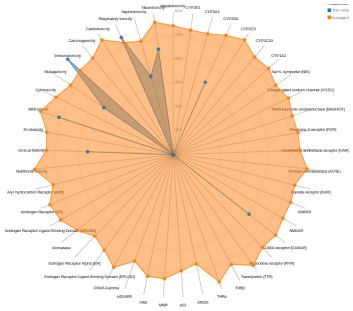
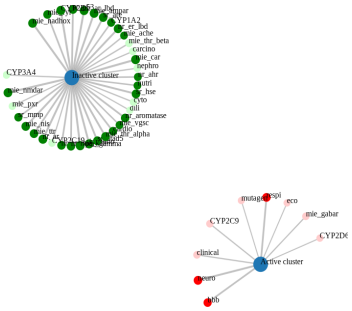
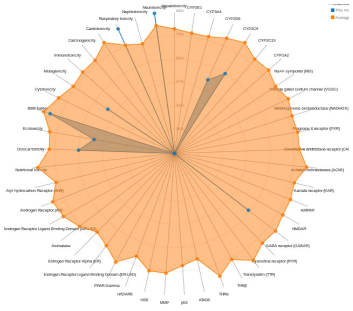
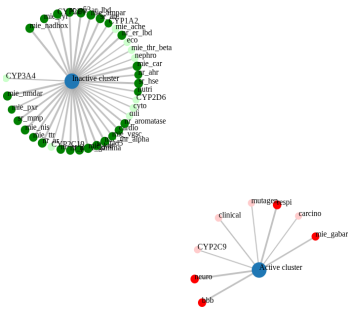
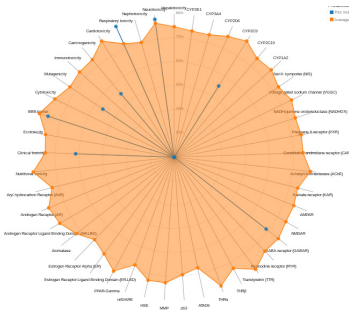
Table 4. *Results of the 15 drugs after SwissADME test, including information on whether it passes or not*

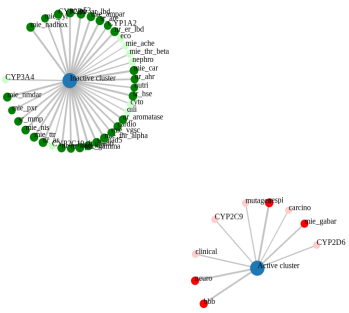
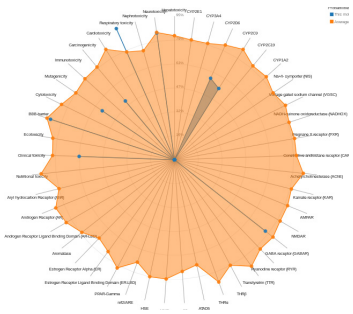
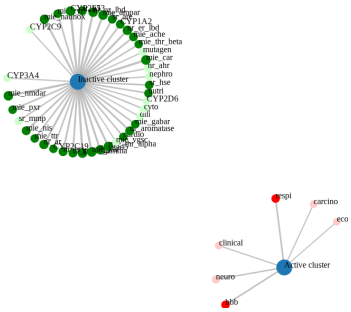
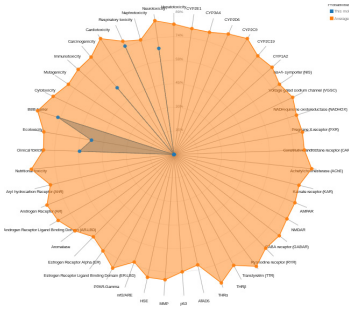
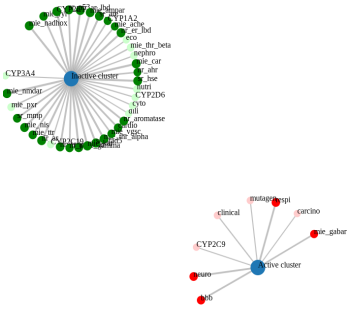
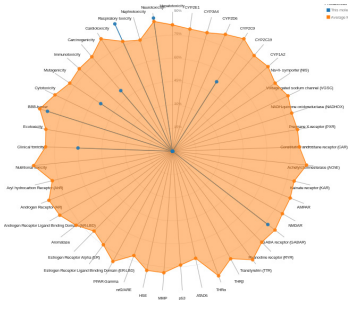
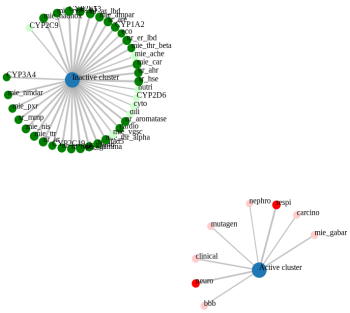
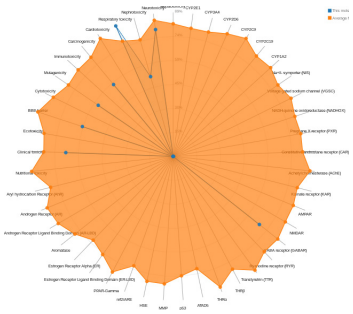
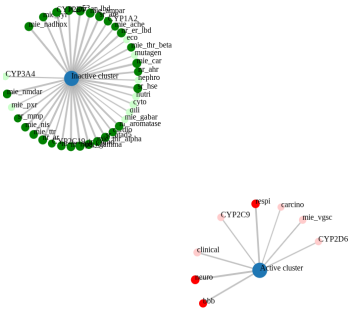
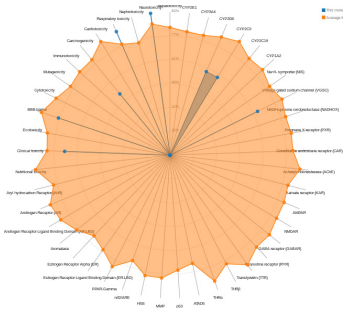
Name	Molecular Weight	Num. H Acceptor	Num. H Donors	CLogP	Agree with Rule
Molport-019–897–498	378.31 g/mol	9	2	2.36	Yes
Molport-051–532–927	328.37 g/mol	6	1	2.03	Yes
Molport-051–462–100	358.79 g/mol	6	1	1.13	Yes
Molport-051–454–708	324.34 g/mol	6	1	0.62	Yes
Molport-051–452–917	338.37 g/mol	6	1	0.94	Yes
Molport-002–621–450	413.52 g/mol	4	3	3.14	Yes
Molport-051–470–239	324.34 g/mol	6	1	0.53	Yes
Molport-020–229–987	343.38 g/mol	6	3	0.19	Yes
Molport-044–334–503	446.43 g/mol	8	2	3.13	Yes
Molport-051–517–110	286.41 g/mol	6	3	0.21	Yes
Molport-046–059–093	432.52 g/mol	5	1	2.45	Yes
Molport-000–814–864	270.24 g/mol	6	4	–0.84	Yes
Molport-039–048–085	265.35 g/mol	4	1	0.99	Yes
Molport-005–953–974	356.81 g/mol	4	2	2.68	Yes
Molport-001–947–650	239.29 g/mol	6	6	–1.71	No

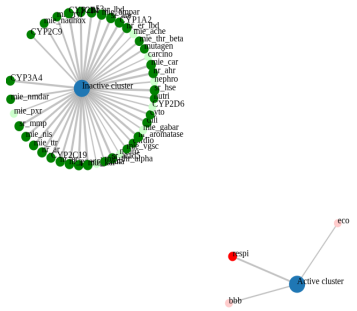
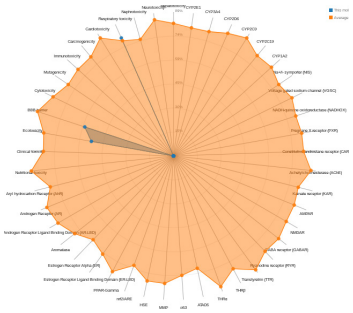
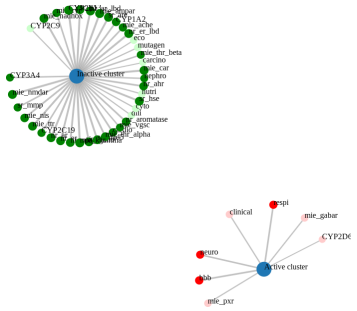
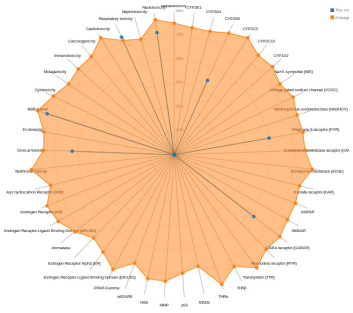
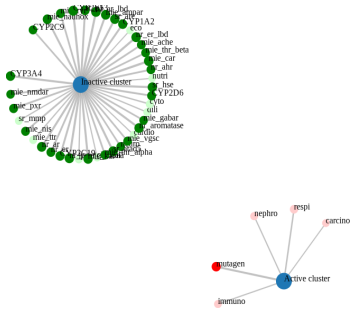
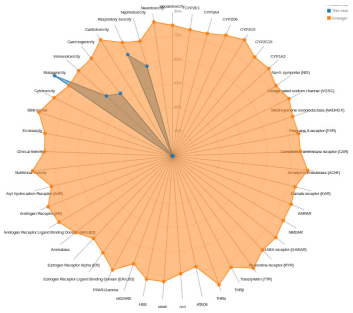
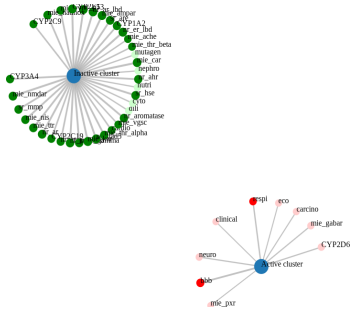
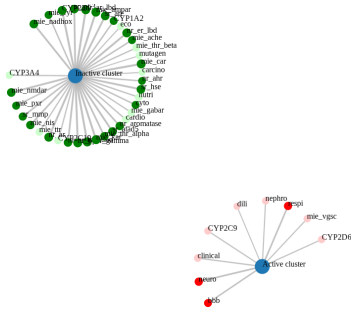
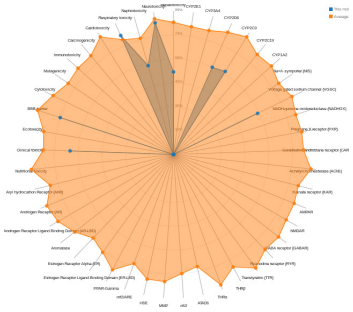
3.2.4 Toxicity Test

Four of the results from the toxicity test will be focused on in this experiment. The Predicted LD50, which is a prediction of how much mg/kg of that substance one would take for a 50% chance of dying, the higher the score, the safer the drug is to the body. In toxicity class, similar to the LD50, the higher score is less toxic, and the lower score is more toxic. Also, every drug is toxic, but this experiment is trying to find out which drugs have a low toxicity so that they wouldn't cause damage to the body when given for TIGIT. The Network Chart shows the toxicity traits of the drug, which is considered safe for the body, along with the toxicity traits that are considered dangerous to the body. Every drug has traits in the dangerous chart.

Table 5. *Results from the 14 drugs' toxicity test. Yellow labels represent the drugs chosen as a result of the experiments*

Name	Predicted LD50	Toxicity Class	Network Chart	Toxicity Radar Chart
Molport-019-897-498	1000mg/kg	4		
Molport-051-532-927	4000mg/kg	5		
Molport-051-462-100	540mg/kg	4		
Molport-051-454-708	540mg/kg	4		

Name	Predicted LD50	Toxicity Class	Network Chart	Toxicity Radar Chart
Molport-051–452–917	635mg/kg	4		
Molport-002–621–450	1500mg/kg	4		
Molport-051–470–239	1100mg/kg	4		
Molport-020–229–987	3500mg/kg	5		
Molport-044–334–503	1000mg/kg	4		

Name	Predicted LD50	Toxicity Class	Network Chart	Toxicity Radar Chart
Molport-051–517–110	2500mg/kg	5		
Molport-046–059–093	210mg/kg	3		
Molport-000–814–864	12400mg/kg	6		
Molport-039–048–085	1300mg/kg	4		
Molport-005–953–974	4000mg/kg	5		

The toxicity radar shows the toxicity level of the drug, represented by the blue dot, compared to the level that is the limit for toxicity on the body. In the end, I have selected three drugs, highlighted in yellow, as the final result of the experiments (Table 5).

Although this experiment was ultimately deemed a success, it still had limitations in terms of resources and experimentation. One of the biggest limitations is doing all of the experiments on the computer using machine learning instead of having actual test subjects. Compared to using the computer, having test subjects can result in better accuracy in certain data. Another limitation is that in the experiment, only 15 drugs were tested. During the Pharmacophore experiment, around 20 million different drugs were generated for each hydrogen acceptor and donor combination, meaning in total, more than 100 million different drugs can bind to TIGIT. However, testing all these could take months or up to a year, hence only 15 were selected for this experiment.

Conclusion

Overall, my experiment on finding a possible immune checkpoint inhibitor drug to bind with TIGIT to prevent it from allowing the immune system to attack early detections of cancer cells was a success, as of the 15 drugs I tested passed the requirements to be a possible inhibitor. In the results of the experiment, I selected three of the drugs based on whether they had a decent SwissParam Score, passed Lipinski's Rule, and had a toxicity class high enough that it wouldn't cause other damage to the body if used. The three drugs might not have been the best in specific experiments, but they fit the requirements well in the overall study. This is a successful experiment, as I was able to find at least one drug that follows these criteria to be used for treating TIGIT. Even though this experiment was very successful, there is much more that can be done to expand it. For example, many other drugs resulting from the pharmacophore can also be found in the same procedure to potentially find even better drugs than the ones in this experiment. Another example is using these drugs on human test-subjects for potentially more accurate data, as this experiment involves all computer and machine learning. There are endless plans that can expand this experiment.

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ENCAPSULATED ONION OIL AS A STABLE SAVORY FLAVOR INGREDIENT: WALL MATERIALS, SPRAY-DRYING TECHNOLOGY AND FOOD APPLICATION POTENTIAL

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Abstract

Onion oil, obtained from Allium cepa L., is a high-impact savory flavoring material characterized by volatile sulfur-containing compounds that provide distinctive fresh, cooked, roasted and pungent onion notes. Despite its sensory value, the direct incorporation of onion oil into industrial food systems is limited by volatility, oxidative sensitivity, intense odor, poor compatibility with dry blends and potential flavor loss during thermal processing and storage. Encapsulation offers a practical technological approach for converting onion oil into a more stable, manageable and application-oriented powder ingredient. Food-grade wall materials such as maltodextrin, gum Arabic, modified starches, proteins and beta-cyclodextrin can improve oil retention, reduce surface oil, support odor masking, enhance powder flowability and enable controlled release in savory matrices. Among available technologies, spray drying is particularly relevant for flavor houses and seasoning manufacturers because it is scalable, continuous and compatible with powdered food systems. This review evaluates encapsulated onion oil as a stable savory flavor ingredient, with emphasis on wall material functionality, spray-drying parameters, volatile retention, powder quality and potential applications in soups, bouillons, sauces, seasonings, snacks, meat products and ready-to-eat foods. Previous work by Bulutoglu on spray-dried fruit powders and bioactive microcapsules provides a relevant technological background for extending encapsulation principles from fruit-based powder systems to volatile savory flavor materials. Overall, encapsulated onion oil represents a promising platform for improving the stability, handling and sensory delivery of onion flavor in industrial food applications.

Keywords: *onion oil; Allium cepa; microencapsulation; spray drying; beta-cyclodextrin; gum Arabic; maltodextrin; savory flavor; controlled release; food applications*

1. Introduction

The food flavoring industry increasingly requires technologies that not only create desirable taste and aroma profiles but also protect volatile compounds during processing, storage and final application. Flavor systems are no longer evaluated only by their initial sensory impact. Their industrial value is also determined by stability, shelf-life behavior, compatibility with food matrices, ease of handling, controlled release and reproducibility in production. These requirements are particularly important for savory flavor systems, where sulfur-containing compounds may provide strong taste direction at very low concentrations but can also be chemically reactive, volatile and difficult to handle.

Onion oil is one of the most important flavoring materials used in savory applications. It provides fresh onion, cooked onion, roasted onion, sulfurous, vegetable-like and meaty background notes depending on its quality, composition, extraction conditions and the food matrix in which it is applied. Onion-derived flavor components are widely used in soups, bouillons, seasonings, sauces, meat products, snacks, ready meals, marinades and plant-based meat analogues. The characteristic sensory profile of onion oil is mainly related to volatile organosulfur compounds, which are formed through biochemical reactions associated with tissue disruption and processing of Allium cepa L. (Ye et al., 2013; Liu et al., 2022).

Although onion oil is a valuable flavoring material, its direct use in industrial food systems is technically challenging. Free onion oil is highly potent and pungent, which makes accurate dosage and homogeneous distribution difficult. Its volatile compounds can be lost during mixing, drying, baking, frying, extrusion, cooking or long-term storage. Some sulfur compounds may oxidize or react with other food components, causing changes in aroma quality over time. In dry seasoning systems, free onion oil may cause caking, uneven distribution, strong headspace odor and poor handling behavior. These limitations create a strong technological need for encapsulated onion oil systems.

Encapsulation is a process in which an active material, referred to as the core, is entrapped, coated or complexed within a protective wall material. In food flavor systems, encapsulation is used to protect volatile compounds, reduce oxidation, mask excessive odor, improve dispersibility, transform liquid flavors into powders and control flavor release during processing or consumption (Gharsallaoui et al., 2007; Jafari et al., 2008; Fernandes et al., 2024). Spray drying, inclusion complexation, coacervation, freeze drying, fluidized bed coating and emulsion-based encapsulation are among the most relevant approaches used for essential oils and flavoring ingredients.

Previous studies by Bulutoglu on spray-dried fruit powders and the effect of spray-drying parameters on bioactive microcapsules provide a relevant technological foundation for extending encapsulation concepts from fruit-based powder systems to volatile savory flavor ingredients (Bulutoglu, 2022 a; Bulutoglu, 2022 b). In both fruit powder production and onion oil encapsulation, the central challenge is similar: sensitive compounds must be converted into stable, industrially useful powders without excessive loss of sensory or functional quality. However, the chemical nature of the core material differs significantly. Fruit concentrates are typically sugar- and acid-rich aqueous systems, whereas onion oil is a hydrophobic, volatile and sulfur-rich flavor material. Therefore, onion oil encapsulation requires specific consideration of emulsion stability, wall material selection, oil retention, powder morphology and release behavior.

The aim of this review is to evaluate encapsulated onion oil as a stable savory flavor ingredient and to discuss the wall materials, encapsulation technologies, spray-drying parameters and food applications that may support its wider use in industrial food systems.

2. Review Methodology

This article was prepared as a narrative technical review rather than a systematic meta-analysis. The literature selection focused on peer-reviewed articles, publisher records and DOI-verifiable sources related to onion essential oil, food flavor microencapsulation, spray drying, wall material selection, oil encapsulation and essential oil stability in food systems. The main search concepts included onion essential oil microcapsules, Allium cepa

essential oil, spray drying food flavors, microencapsulation of food oils, beta-cyclodextrin flavor encapsulation, gum Arabic spray drying, maltodextrin flavor encapsulation and essential oil applications in food products.

Preference was given to studies directly related to onion oil or onion-derived ingredients where available. Broader spray-drying and microencapsulation literature was included when onion-specific data were limited but the technological principles were applicable to volatile flavor oils. Previous published work by Bulutoglu on spray-dried fruit powders and spray-drying parameters was included as contextual background for discussing the transfer of encapsulation principles from fruit-based powders to savory flavor systems (Bulutoglu, 2022a; Bulutoglu, 2022b).

3. Chemical and Technological Characteristics of Onion Oil

Onion oil is generally obtained from onion bulbs through extraction processes such as steam distillation, solvent extraction or supercritical carbon dioxide extraction. Its composition varies depending on onion variety, maturity, agricultural conditions, extraction method, processing temperature and storage conditions. The most important sensory-active compounds are sulfur-containing volatiles, which are responsible for the distinctive pungent, lachrymatory, fresh onion and cooked onion characteristics of onion-derived materials (Ye et al., 2013; Liu et al., 2022).

When onion tissue is disrupted, enzymatic pathways involving alliinase and related reactions lead to the formation of sulfurous intermediates and volatile compounds. These compounds may include sulfides, disulfides, trisulfides, thiosulfinates and other sulfur-containing molecules. Many of these compounds have low odor thresholds, meaning that even small changes in concentration can have a significant impact on the perceived aroma profile.

From a flavor creation perspective, onion oil should not be considered a simple single-note raw material. It can provide different sensory effects depending on dosage and matrix. At low levels, onion oil may contribute background savoriness, cooked vegetable depth and kitchen-like authenticity. At higher levels, it may become sharp, pungent, sulfurous or dominant. In thermally processed foods, some onion notes may shift toward cooked, roasted or savory directions, while fresh top notes may decrease.

Onion oil has also attracted scientific interest because of its potential antimicrobial and antioxidant activity. Ye et al. (2013) reported antimicrobial and antioxidant activities for Allium cepa essential oil, suggesting that onion oil may have relevance beyond its sensory contribution. However, functional effects depend on concentration, matrix composition, target microorganisms, regulatory status and sensory acceptability. In practical food flavoring, the primary commercial value of onion oil remains its ability to deliver a characteristic and recognizable onion profile in savory systems.

The same chemical features that make onion oil valuable also create formulation challenges. Volatile sulfur compounds can be lost, oxidized or transformed during processing and storage. The strong odor of onion oil can create cross-contamination risk in production environments. Its liquid and hydrophobic nature limits compatibility with dry powder blends. These issues justify the use of encapsulation as a technological strategy.

4. Challenges in the Direct Use of Free Onion Oil

The major aroma-active compounds in onion oil are volatile. During industrial food processing, free onion oil can evaporate or degrade, especially under high temperature, aeration, open mixing, spray drying, baking, frying or extrusion conditions. Volatility and instability under light, oxygen, moisture and temperature exposure are general limitations of essential oils and oleoresins in food systems (Fernandes et al., 2024). In dry seasonings, free oil may also migrate to the surface of carrier particles and gradually lose intensity during storage. This may lead to weaker flavor delivery in the final product and inconsistent sensory performance between production batches.

Sulfur compounds are reactive and may undergo oxidation or interact with proteins, carbohydrates, lipids, minerals and packaging materials. These reactions may modify the original onion character and generate off-

notes. In complex savory systems, onion oil may be combined with garlic, yeast extract, Maillard reaction flavors, hydrolyzed vegetable protein, meat flavors or spice extracts. Although such matrices may improve the final flavor profile, they may also increase the possibility of chemical interaction.

Free onion oil has a strong odor and can create sensory carry-over in manufacturing environments. Open handling may be unpleasant for operators and may contaminate equipment, packaging or adjacent products. Excessive headspace odor in finished packaging may also be undesirable. Encapsulation can reduce immediate odor impact by entrapping the oil within a protective wall while still allowing release during hydration, heating or mastication. Odor masking and improved stability are among the functional benefits commonly associated with essential oil microencapsulation (Fernandes et al., 2024).

Many savory products are produced as dry blends. Examples include soup powders, bouillon powders, instant sauce bases, snack seasonings and spice blends. Free onion oil is difficult to distribute uniformly in such systems unless it is first plated onto a carrier. However, simple plating onto maltodextrin, salt, starch or other carriers usually leaves part of the oil on the surface, increasing exposure to oxygen and accelerating aroma loss. Encapsulation can provide better protection than simple adsorption by reducing surface oil and improving matrix integration.

Onion oil used in sauces, gravies, instant soups or ready meals may be exposed to heating, freezing, thawing, microwave cooking or hot filling. Free oil may lose intensity or change character during these processes. Encapsulated systems, particularly those based on spray-dried matrices or cyclodextrin inclusion, may provide improved process tolerance by reducing direct exposure of volatile compounds to air, heat and reactive matrix components.

5. Principles of Onion Oil Encapsulation

The encapsulation of onion oil requires the formation of a stable system in which the oil is dispersed, entrapped, complexed or coated within a protective material. In spray drying, onion oil is usually emulsified in an aqueous wall material solution. The emulsion is then atomized into hot air, where water evaporates rapidly and dry microcapsules are formed. Ideally, the oil remains within the particle rather than on the surface, since low surface oil is associated with improved oxidative stability and better encapsulation quality in flavor oil powders (Jafari et al., 2008; Mohammed et al., 2020).

The performance of an encapsulated onion oil powder depends on several key properties: encapsulation efficiency, surface oil content, moisture content, water activity, glass transition behavior, solubility, dispersibility, bulk density, flowability, particle morphology and sensory release. For onion oil specifically, successful encapsulation should not only protect the oil but also reduce excessive pungency during handling. A high-quality encapsulated onion oil powder should be free-flowing, low in surface oil, stable during storage and capable of releasing a recognizable onion profile when applied to food.

6. Encapsulation Technologies for Onion Oil

Spray drying is the most industrially relevant method for onion oil encapsulation. It is widely used in the flavor industry because it can convert emulsions into powders in a continuous and cost-effective process. Reineccius (2004) described spray drying as a major technique for dry flavor production, and later reviews confirm its broad use for microencapsulation of food ingredients, oils and flavor compounds (Gharsallaoui et al., 2007; Jafari et al., 2008; Mohammed et al., 2020). The method is compatible with maltodextrin, gum Arabic, modified starches, proteins and combinations of these materials.

In onion oil encapsulation, the process generally involves preparing an oil-in-water emulsion using wall materials and emulsifiers, homogenizing the emulsion to reduce droplet size, and drying the emulsion under controlled inlet and outlet air temperatures. Smaller and more uniform emulsion droplets generally support better encapsulation because they reduce oil migration and improve distribution within the wall matrix. The main advantage of spray drying is scalability, while the main limitation is heat exposure. Therefore, carrier selection, emulsion stability and operating conditions must be considered to-

gether rather than independently (Gharsallaoui et al., 2007; Jafari et al., 2008).

Beta-cyclodextrin is a cyclic oligosaccharide with a hydrophobic internal cavity and a hydrophilic external surface. This structure enables it to form inclusion complexes with hydrophobic flavor molecules. For onion oil, beta-cyclodextrin can help entrap volatile sulfur compounds, reduce odor intensity and improve thermal and storage stability. Wang et al. (2018) evaluated onion essential oil microcapsules prepared by spray drying and reported that Arabic gum, beta-cyclodextrin and maltodextrin were relevant wall materials for optimizing microencapsulation efficiency and powder quality.

Freeze drying, coacervation, complex coacervation and fluidized bed coating may also be applied to flavor oils. Freeze drying can preserve heat-sensitive materials but is slower and more expensive than spray drying. Coacervation can provide controlled release but is more complex and may require additional stabilization steps. Fluidized bed processes may improve granulation, flowability or coating quality, although the protection level depends strongly on coating performance and surface oil control.

7. Wall Materials Used in Onion Oil Encapsulation

Maltodextrin is one of the most commonly used wall materials in spray drying. It is relatively inexpensive, bland in taste, widely available and provides useful film-forming and glass-forming properties. In flavor encapsulation, maltodextrin helps create a dry matrix around oil droplets and contributes to low stickiness when the dextrose equivalent is properly selected (Gharsallaoui et al., 2007; Jafari et al., 2008; Mohammed et al., 2020). However, maltodextrin has limited emulsifying capacity and is often combined with gum Arabic, modified starches or proteins.

Gum Arabic is a highly valued encapsulating agent because of its emulsifying ability, solubility and film-forming properties. It can stabilize oil-in-water emulsions and reduce oil migration during spray drying. In onion oil encapsulation, gum Arabic can contribute to better oil retention and smoother particle morphology. Its main limitations are cost and supply variability, but it remains a strong candidate in high-impact savory flavor systems.

Beta-cyclodextrin is especially suitable for volatile flavor stabilization because it can form inclusion complexes with hydrophobic molecules. In onion oil systems, it can reduce pungent odor, improve retention and support controlled release. Its combination with gum Arabic may provide both molecular inclusion and emulsion stabilization, making it one of the most promising wall material strategies for onion essential oil (Wang et al., 2018).

Modified starches are widely used in flavor encapsulation because they can offer good emulsification, low viscosity at useful solids levels and strong compatibility with spray drying. Proteins such as whey protein isolate, whey protein concentrate, caseinate and plant proteins may also contribute emulsification and film formation. However, proteins may introduce allergen, labeling or flavor interaction considerations (Jafari et al., 2008; Mohammed et al., 2020).

8. Comparative Evaluation of Wall Materials

The selection of wall material is a central formulation decision because onion oil is hydrophobic, volatile and sulfur-rich. No single wall material provides all desirable properties. Therefore, practical industrial systems often rely on combinations of carbohydrates, gums, cyclodextrins, modified starches and proteins.

Table 1. *Food-grade wall materials and their expected performance in onion oil encapsulation*

Wall material	Main technological role	Expected advantages	Possible limitations	Industrial suitability
Maltodextrin	Matrix former and drying carrier	Low cost, bland taste, good glass-forming ability, suitable for spray drying	Weak emulsifying capacity when used alone; may increase surface oil if not combined with emulsifier	High, especially in cost-sensitive powder systems

Wall material	Main technological role	Expected advantages	Possible limitations	Industrial suitability
Gum Arabic	Emulsifier and film-forming wall material	Strong emulsion stabilization, good solubility, improved oil retention	Higher cost and supply variability	High for premium flavor encapsulation
Beta-cyclodextrin	Inclusion complex former	Strong potential for volatile retention, odor masking and controlled release	Cost, dosage and regulatory/labeling considerations	Medium to high for high-impact savory top notes
Modified starch	Emulsifying carrier and wall former	Good process compatibility, low viscosity at useful solids, possible gum Arabic replacement	Performance depends strongly on starch type and modification	High for industrial spray-dried flavors
Whey/ caseinate proteins	Interfacial film formation and emulsion stabilization	Good oil droplet stabilization, possible reduction of surface oil	Allergen/labeling issues; possible flavor interaction	Medium, depending on application and label requirement
Plant proteins	Emulsion stabilization and label-friendly positioning	Useful for vegan or plant-based savory applications	Solubility, beany notes and process variability may occur	Emerging; requires application-specific optimization

Figure 1. *Comparative technical roles of selected wall materials in onion oil encapsulation. Scores represent a literature-based technical interpretation rather than a direct experimental comparison. Scoring scale: 1 = low expected contribution; 5 = high expected contribution*

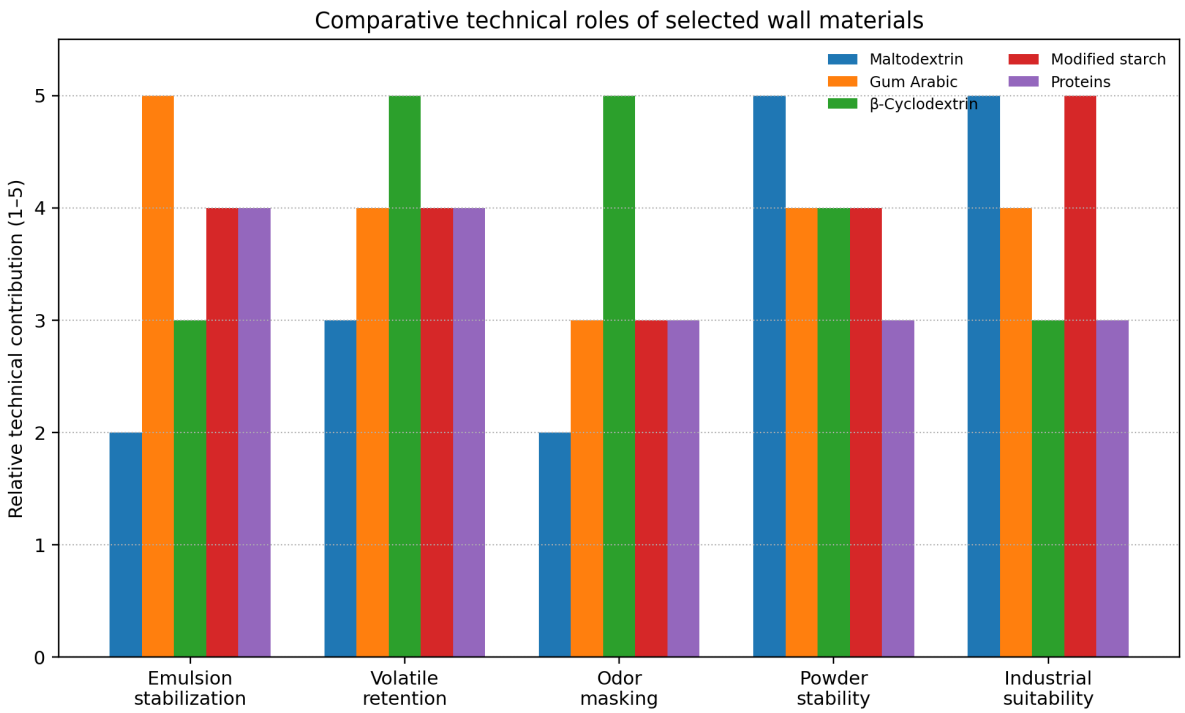


Table 1 summarizes the expected technological contribution of major food-grade wall materials.

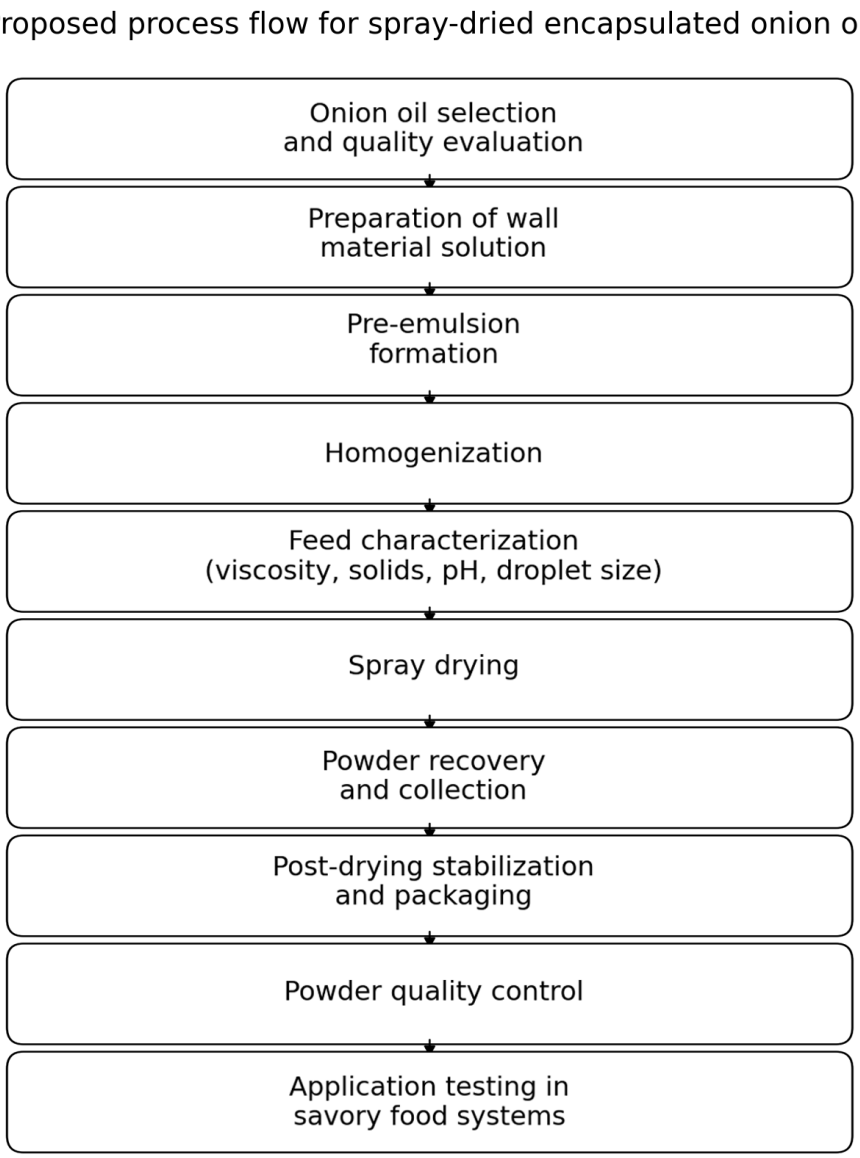
A combined system is often more realistic than a single wall material. For example, maltodextrin may provide economical matrix formation, gum Arabic or modified starch may stabilize the emulsion, and beta-cyclodextrin may improve volatile retention. The optimum system depends on the target food application, oil loading, sensory release requirement and cost position.

A graphical comparison of commonly used wall materials may help illustrate the formulation logic of onion oil encapsulation systems. In the present review, this comparison should not be interpreted as a direct experimental ranking under identical laboratory conditions, but rather as a literature-based technical assessment of the relative contributions of selected encapsulating agents.

9. Proposed Industrial Process Flow

From an industrial perspective, onion oil encapsulation should be understood as a multi-step process rather than a single drying operation.

Figure 2. *Proposed process flow for the production of spray-dried encapsulated onion oil. The process includes oil selection, wall material preparation, emulsion formation, homogenization, feed characterization, spray drying, powder collection, stabilization, quality control and application testing*



The quality of the final powder depends not only on spray-drying conditions, but also on the quality of the onion oil, the selection and hydration of wall materials, the stability of the emulsion system, homogenization efficiency and post-drying handling. For this reason, a process-flow representation is valuable in review articles, as it links formulation design to powder performance and final application behavior in savory food systems.

This process flow emphasizes that encapsulated onion oil should be evaluated as an application ingredient rather than only as a powder. Analytical retention must be supported by sensory performance in the final food matrix.

10. Effect of Processing Parameters on Powder Quality

The quality of encapsulated onion oil depends not only on wall materials but also on processing conditions. In spray drying, the most important parameters include inlet air temperature, outlet air temperature, feed solids content, oil-to-wall ratio, emulsion droplet size, feed flow rate, atomization pressure and drying air humidity (Reineccius, 2004; Gharsallaoui et al., 2007; Jafari et al., 2008).

A higher inlet temperature may increase drying rate and reduce moisture content, but it can also increase the loss of volatile onion compounds. A lower inlet temperature may improve retention but can lead to incomplete drying, wall deposition or sticky powder. Therefore, onion oil encapsulation requires a balance between sufficient drying and flavor preservation. Similar relationships between carrier concentration, drying temperature, powder stability and bioactive retention have been discussed in spray-dried fruit and bioactive powder systems (Bulutoglu, 2022 a; Bulutoglu, 2022 b).

Feed solids content also influences powder quality. Higher solids may improve drying efficiency and reduce energy consumption, but excessive viscosity can reduce atomization quality and increase particle size. The oil-to-wall ratio affects both cost and retention. A higher oil load may improve flavor impact per kilogram of powder but can increase surface oil and reduce storage stability.

Emulsion stability is one of the most critical factors. If the emulsion separates before or during spray drying, oil retention will be poor. Homogenization conditions should produce small and uniform droplets without causing excessive foaming or oxidation. The use of gum Arabic, modified starch or protein-based emulsifiers can improve emulsion stability and is frequently discussed as a major factor influencing encapsulation efficiency in food flavor and oil systems (Jafari et al., 2008; Mohammed et al., 2020).

Particle morphology is another important indicator. Smooth and continuous particles are preferred because they limit oxygen diffusion and surface oil exposure. Cracked or collapsed particles may release onion oil prematurely and reduce shelf life. Scanning electron microscopy is commonly used in encapsulation studies to evaluate particle morphology.

11. Stability, Controlled Release and Sensory Performance

The main purpose of onion oil encapsulation is to improve stability without losing sensory identity. Stability can be evaluated through storage tests, volatile retention analysis, sensory evaluation, oxidation markers and moisture sorption behavior. Because onion oil is highly odor-active, sensory evaluation is particularly important. A powder may show good analytical retention but still fail if the released flavor is too weak, too pungent or unbalanced. This application-based evaluation is consistent with broader recommendations that encapsulation performance should be assessed through both physicochemical and functional behavior in food systems (Gharsallaoui et al., 2007; Fernandes et al., 2024).

Controlled release is a key advantage of encapsulation. In dry powder blends, the onion character should remain protected during storage. During food preparation or consumption, the flavor should be released through hydration, heat, shear or mastication. Different wall materials create different release profiles. Maltodextrin-based matrices may release rapidly in water. Gum Arabic and modified starch systems may provide balanced release. Cyclodextrin complexes may release flavor more gradually depending on temperature, moisture and matrix competition.

For savory foods, release timing is important. In instant soup, the flavor should

develop rapidly after hot water addition. In snack seasonings, release occurs during chewing and interaction with saliva. In meat products or ready meals, onion flavor should survive processing and then become perceptible during heating or consumption. A successful encapsulated onion oil system must therefore be designed according to the intended application, not only according to encapsulation efficiency.

12. Food Application Potential

Encapsulated onion oil is highly suitable for powdered soups and bouillons. These products require dry ingredients with good flowability, long shelf life and rapid flavor release in hot water. Onion is a fundamental background note in many bouillon systems, especially chicken, beef, vegetable and tomato profiles. Encapsulated onion oil can provide consistent onion character while reducing flavor loss during storage.

Snack seasonings require powdered ingredients that can be blended with salt, spices, flavor enhancers, yeast extracts and oil-based carriers. Free onion oil may create clumping, uneven distribution and strong odor during production. Encapsulated onion oil can improve handling and enable more controlled delivery on chips, crackers, nuts and extruded snacks.

Onion flavor is central to many sauces, gravies and culinary bases. Encapsulation can help onion oil withstand thermal processing, freezing and reheating. Cyclodextrin-based systems may be particularly useful in products exposed to microwave heating or steam-table holding, where volatile retention is difficult.

Onion notes are commonly used in meat seasonings, cooked meat flavors and plant-based meat analogues. Encapsulated onion oil can contribute to authentic cooked culinary character while improving distribution in dry premixes. It may also help reduce flavor loss during cooking.

In ready-to-eat and ready-to-cook products, encapsulated onion oil can support consistent flavor release after heating. It may be used in dry sauce bases, noodle seasonings, rice meals, frozen meals and dehydrated culinary mixes. Essential oil and oleoresin microcapsules have been described as suitable for a broad range of food applications, including sauces, meat products, bakery products and other processed systems (Fernandes et al., 2024).

13. Industrial Relevance for Flavor Houses

For flavor houses, encapsulated onion oil is not merely a raw material but a technology platform. It can be used to create differentiated savory systems with better stability, cleaner handling and improved process performance. The development of such powders requires collaboration between flavor creation, application, process engineering and quality control.

The industrial value of encapsulated onion oil can be summarized in five areas: stability, handling, application flexibility, controlled release and standardization. A flavor house with spray drying and encapsulation capability can use onion oil as a model system for other savory volatile materials such as garlic oil, leek oil, roasted onion top notes, meat reaction flavors and spice oleoresins. The same technological principles may also be applied to natural flavor systems, clean-label culinary bases and high-impact top notes.

14. Future Perspectives

Future research on encapsulated onion oil should focus on the relationship between encapsulation efficiency, volatile profile and sensory release. Many encapsulation studies report high oil retention but do not sufficiently evaluate whether the final flavor profile remains authentic. For onion oil, this is especially important because the balance between fresh, cooked, sulfurous and roasted notes can change during processing.

More work is also needed on storage stability under realistic industrial conditions. Temperature, humidity, oxygen exposure and packaging type can strongly affect powder performance. Accelerated shelf-life studies should be supported by sensory panels and instrumental volatile analysis.

Another promising research area is the use of combined wall systems. Gum Arabic and beta-cyclodextrin may provide strong performance, but cost and supply should be considered. Maltodextrin-modified starch-protein systems may offer more economical alternatives. Plant protein systems may

become more important as the market grows for vegan and allergen-conscious savory products.

Finally, clean-label expectations should be considered carefully. Encapsulation often requires carriers and processing aids, while some customers prefer shorter ingredient lists. Future development must balance technological performance with label expectations, regulatory compliance and customer requirements.

15. Conclusion

Onion oil is a high-impact savory flavor material with strong relevance for soups, bouillons, seasonings, sauces, meat products, snacks and ready-to-eat foods. Its sensory value is mainly associated with volatile sulfur-containing compounds that provide characteristic onion aroma at low dosage levels. However, these same compounds also create technological limitations, including volatility, oxidation sensitivity, odor intensity, poor handling properties and flavor losses during processing and storage.

Encapsulation provides a practical solution by transforming onion oil into a more stable, manageable and application-compatible ingredient. Food-grade wall materials such as maltodextrin, gum Arabic, modified starches, proteins and beta-cyclodextrin can contribute to oil retention, surface oil reduction, odor masking, powder stability and controlled release. Spray drying remains the most industrially relevant encapsulation approach because it is scalable, continuous and compatible with dry flavor and seasoning systems. Nevertheless, successful onion oil encapsulation depends not only on the drying process itself, but also on oil quality, wall material functionality, emulsion stability, oil-to-wall ratio, feed solids, atomization behavior and post-drying handling.

For industrial flavor development, encapsulated onion oil should be evaluated beyond encapsulation efficiency alone. A successful product must demonstrate acceptable powder properties, storage stability and authentic sensory release in the intended food matrix. Future studies should therefore combine volatile analysis, surface oil measurement, water activity, particle morphology, accelerated shelf-life testing and application-based sensory evaluation. From this perspective, encapsulated onion oil can be considered a promising bridge between flavor chemistry and food process technology, offering a pathway to more stable, controllable and industrially useful savory flavor systems.

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Conflict of Interest

The author is affiliated with DKT Flavor and Taste, a company operating in the flavor and food ingredients sector. This affiliation is disclosed for transparency. The author declares no additional conflict of interest related to the preparation of this review.

Data Availability Statement

This article was prepared on the basis of previously published literature and author interpretation, and it was additionally informed by preliminary laboratory trials carried out at DKT Flavor laboratories. These internal trials supported the technical evaluation of onion oil encapsulation systems; however, as the manuscript is structured as a review article rather than a full experimental study, no standalone experimental dataset is presented.

Author Contributions

Efe Bulutoglu conceptualized the topic, evaluated the literature, interpreted the industrial relevance of onion oil encapsulation and prepared the manuscript.

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Section 3. Economics and Management

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CHARACTERISTICS OF TEXTILE FACILITIES AND ISSUES ARISING IN FIRE PREVENTION AND FIGHTING

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Abstract

A textile facility is a legally constructed and operated building, structure, or location where one or more stages of the textile production chain are carried out, including fiber processing, spinning, weaving, dyeing, printing, finishing, industrial sewing, raw material and finished product warehousing, and related auxiliary activities. Textile facilities are typically characterized by containing a large amount of flammable materials, such as cotton, fabrics, synthetic fibers, and dyeing chemicals; having a high density of machinery and equipment; and concentrating a large number of workers. Textile factories are places with enclosed production spaces, limited ventilation, and complex electrical systems... This article analyzes the characteristics of textile factories and the current state of fire prevention and fighting, pointing out existing problems and limitations in this area, and then proposing solutions to improve the effectiveness of fire prevention and fighting in textile factories.

Keywords: *Textile factories; characteristics of textile factories; fire prevention and fighting*

1. Introduction

The textile and garment industry currently plays a key role in the national economic structure, identified as one of the key export sectors, making a significant contribution to GDP growth and export turnover. In particular, the industry is of great significance in creating sustainable livelihoods for millions of workers, especially in concentrated industrial zones and rural areas, where light industry is a driving force for local economic development. As of December 2025, Vietnam had over 6,892 active textile and garment production facilities, widely distributed across key economic regions such as the Red River Delta, Southeast, North Central, and Central Coastal regions, thus contributing to the development of our national economy. However, in addition to the contribution of textile and garment facilities to the economy, these facilities also pose many fire and explosion risks due to their specific characteristics of

containing large quantities of flammable materials, such as cotton, fabrics, synthetic fibers, and dyeing chemicals; It is a place with a high density of machinery and equipment; it is a place where a large number of workers are concentrated. Textile factories are places with enclosed production spaces, limited ventilation, and complex electrical systems... According to statistics, from 2019 to the end of 2025, the number of fires in textile factories was 244 (accounting for 0.99%) of the total number of fires in Vietnam, resulting in 39 deaths (accounting for 5.64%), 104 injuries (accounting for 13.38%), and estimated property damage of approximately VND 735.38 billion (accounting for 12.7%). Many fires caused serious damage to people and property, such as: the fire on June 2, 2023, at the factory of Concord Textile Corporation Vietnam Co., Ltd. – specializing in yarn spinning and textile manufacturing, Nhon Trach 2 Industrial Park, Dong Nai province, which destroyed 1000 m2 of factory space, causing serious property damage; The fire occurred at noon on July 11, 2023 at a textile company in My Phuoc 3 Industrial Park, Binh Duong province (now Ho Chi Minh City), burning down about 1,500m² – 4,000m² of factory buildings;... (Fire and Rescue Police Department, *Summary report on work from 2021 to the end of 2025)*. Due to the specific characteristics of textile facilities, the main causes of fires in this type of facility are electrical equipment malfunctions due to overload; in addition, the cause due to the carelessness of workers in textile facilities is also a matter of concern; on the other hand, the cause due to technical malfunctions and violations of fire prevention regulations also account for a relatively high percentage. To limit fires in textile facilities, it is necessary to study and analyze the specific characteristics of textile facilities and on that basis propose synchronized solutions to organize fire prevention work for this type of facility.

2. Research Results

2.1. Characteristics of Textile and Garment Facilities

Characteristics of Raw Materials and Goods: The main raw materials of the textile and garment industry are cotton, yarn, fabric, and accessories (thread, foam, sponge, paper packaging, nylon, etc.). These are all flammable substances with a rapid flame spread rate and produce a lot of smoke and toxic gases when burned. In particular, synthetic fabrics can melt, drip, and spread fire to other areas when burned. Cotton dust and yarn dust accumulating in the air or adhering to equipment can increase the risk of smoldering fires, spreading fires, or even dust explosions under certain conditions. Warehouses storing raw materials and finished products often have a high flammable load; if not properly divided and fire-resistant, they can cause fires to spread over a large area.

Characteristics of Technology and Equipment: The textile and garment production process includes many consecutive stages such as spinning, weaving, dyeing, drying, cutting, sewing, ironing, and packaging. In this system, the machinery uses high-power electric motors and operates continuously. The processes of heat pressing and drying utilize high temperatures. The electrical system often has a high density of wires, posing a high risk of overload and short circuits if not regularly inspected and maintained. Production lines are often arranged close together to save space, making it difficult to create safe distances for fire prevention and evacuation in case of an emergency.

Regarding architecture and construction: many textile and garment facilities, especially small and medium-sized enterprises, utilize renovated warehouses, residential buildings, or structures that do not meet fire safety standards. Some common shortcomings include: lack of fire containment and fire spread prevention solutions between production areas and storage areas; insufficient number and width of escape routes, or obstruction by goods; and the absence or ineffectiveness of automatic fire alarm and extinguishing systems.

Characteristics of labor organization: Textile factories typically employ a large number of workers, concentrated in shifts, working in enclosed spaces. This leads to: a high risk of casualties in the event of a fire; a complacent attitude among workers due to familiarity with environments containing many flammable materials; and limited awareness and skills in handling fire emergencies among some workers.

2.2. Regarding the current state of fire prevention work in textile and garment establishments

The Vietnam Fire Prevention and Rescue Police Force has organized fire prevention work, specifically: proactively advising the Government and the Ministry of Public Security to issue many legal documents, directives, and guidelines related to organizing fire prevention work in textile and garment establishments... Along with that, the Fire Prevention and Rescue Police Force of local police departments has strengthened measures to organize fire prevention work in textile and garment establishments, specifically: propaganda, building a movement for all citizens to participate in fire prevention activities, appraising designs and inspecting acceptance work on fire prevention, building and organizing fire prevention and rescue forces at textile and garment establishments... According to statistics from 2019 to the end of 2025, the Fire Prevention and Rescue Police Force of local police departments has actively organized fire prevention work in textile and garment establishments, specifically: advising competent authorities to organize the issuance of 10,656 directives, official letters, and documents on fire prevention and fighting work in general and fire prevention work for textile and garment establishments in particular; organized design appraisal and inspection of acceptance work for 6,545 textile and garment establishments; organized propaganda work, including writing 12,407 news articles on fire prevention and fighting for textile and garment establishments, building 2,753 reports and documentaries on fire prevention and fighting,... (Fire and Rescue Police Department, *Summary report on work from 2021 to the end of 2025)*. From there, created many positive changes in organizing fire prevention work for textile and garment establishments, curbing the number of fires in textile and garment establishments.

Despite the achievements, fire prevention work in textile and garment facilities still has certain limitations and shortcomings, specifically: the quality of advisory and proposal work is not truly high; the dissemination and education of knowledge and laws on fire prevention and fighting for textile and garment facilities have not been carried out regularly or extensively; the process of receiving and resolving administrative procedures in the design appraisal and acceptance inspection of textile and garment facility constructions is not yet consistent and synchronized, leading to many difficulties for investors and businesses in complying with regulations on design appraisal and acceptance inspection; The inspection and detection of fire safety violations in textile and garment establishments have not been timely, the handling of violations has not been strict, and there has been a lack of focus on inspecting the remediation of administrative violations related to fire safety and rescue in textile and garment establishments;... The reasons for these limitations and shortcomings are: the awareness of some leaders and commanders is not high enough, and they have not directed decisively in organizing fire prevention work for textile and garment establishments; the staffing of the force performing fire prevention tasks in general and for textile and garment establishments in particular currently does not meet the requirements in terms of quantity and standards as stipulated in Circular No. 37/2025/TT-BCA; some investors and heads of textile and garment establishments have not strictly fulfilled their responsibilities; Infrequent reviews and summaries of fire prevention work at textile and garment facilities have not been conducted, resulting in a lack of comprehensive analysis of prominent issues in this area. This has hindered the development of solutions to address urgent problems in these facilities. Some agencies and departments have not shown genuine interest, provided close guidance, or established coordination mechanisms. Even with coordination, there is no mechanism for monitoring and supervising the work carried out.

2.3. Regarding measures to improve the effectiveness of fire prevention work organization for textile and garment establishments in the future

1) Proactively organize the gathering of information, advise and propose to competent authorities to issue and organize the implementation of legal regulations on fire prevention, firefighting and rescue for textile and garment establishments: organize and seriously implement basic investigation work to gather information on textile and garment establishments according to the law and guid-

ance on basic professional work of the People's Police force, including building information sheets for managing textile and garment establishments, collecting necessary information such as the nature of activities, owner of the establishment, characteristics of fire and explosion hazards... of textile and garment establishments to serve digital transformation work, build digitized data in organizing fire prevention work for textile and garment establishments, thereby helping the Fire Prevention and Rescue Police force in organizing fire prevention work for textile and garment establishments to be convenient, easy, quick and accurate to serve the advisory and proposal work; Design appraisal and acceptance testing; fire safety inspection, building fire fighting and rescue forces... The Fire Police and Rescue Forces of local police departments proactively advise the Provincial Police Directorate to issue a plan to implement the regulations of the above documents to police units in their jurisdiction, with the core being officers assigned to organize fire prevention work for textile and garment facilities.

2) Strengthen leadership and guidance in the issuance and organization of the implementation of legal regulations on fire prevention and rescue for the organization of fire prevention work for textile and garment facilities, including: focusing on issuing guiding documents to quickly and effectively implement the provisions of the Law on Fire Prevention and Rescue and accompanying legal documents for textile and garment facilities. At the same time, strengthen leadership and guidance by issuing guiding documents on the organization of fire prevention work for textile and garment facilities. Leaders and commanders should regularly inspect and supervise fire prevention work at textile and garment facilities. Leaders and commanders within the Fire Prevention and Rescue Police force need to fully understand their roles and responsibilities. Furthermore, within their functions, duties, and authority, they must be familiar with the legal regulations on fire prevention and rescue, thereby making sound leadership and guidance decisions, effectively resolving issues, and ensuring compliance with the law. This will help improve the quality of fire prevention work at textile and garment facilities in various units and localities. Unit leaders and commanders should strengthen their guidance, inspection, and supervision of officers responsible for organizing fire prevention work at textile and garment facilities in carrying out their assigned tasks. In particular, they should inspect the fire prevention work documentation for textile and garment facilities, specifically: checking design appraisal documents and inspecting acceptance procedures. Reviewing propaganda records and building a nationwide movement for public participation in fire prevention and fighting activities; reviewing inspection reports and decisions on administrative penalties; reviewing records on the establishment and assignment of responsibilities to grassroots fire prevention and rescue forces to quickly identify shortcomings and limitations in the organization of fire prevention work and promptly direct the implementation of corrective measures.

3) Improve the quality of organization of design appraisal and inspection of fire prevention and fighting for textile and garment facilities: assign competent and qualified staff to perform the task of receiving design appraisal dossiers at the one-stop service department to serve the receiving and inspection of design appraisal dossiers to create favorable conditions for businesses in submitting design appraisal dossiers; assign qualified staff to perform the task of appraising fire prevention and fighting designs for textile and garment facilities. Furthermore, each officer assigned to conduct fire safety design review in general, and for textile and garment facilities in particular, needs to proactively update and study the latest legal regulations on fire prevention and rescue, as well as related legal documents, standards, and technical regulations on fire safety. They should develop specific comparison tables of the legal provisions for each type of facility, such as a comparison table for design review of textile and garment facilities, etc. The construction inspection process must ensure compliance with legal regulations. Only when all fire safety requirements are fully met should acceptance and operation be approved. For textile and garment manufacturing projects and facilities that have already commenced operations without fire safety design appraisal or fire safety acceptance testing, during the process of coordinating with

relevant authorities to resolve the issue, it is necessary to recommend that the investor allocate funds for the installation of fire safety equipment and related technical systems such as smoke extraction systems for corridors and basements, pressurized stairwell systems, and fire-resistant doors for stairwells, etc.

4) Organizing the construction and compilation of documents; diversifying forms; building models and handbooks for propaganda, dissemination, and education of knowledge and laws on fire prevention, firefighting, and rescue, and building a nationwide movement to participate in fire prevention and firefighting activities for textile and garment facilities: one of the factors that directly impacts the propaganda and dissemination of laws and knowledge on fire prevention and firefighting is the content of the propaganda. The content of the propaganda and dissemination is profound, easy to understand, and practical, so it always attracts the attention of listeners and readers, etc., contributing to the success of the propaganda and dissemination of laws and knowledge on fire prevention and firefighting. Selecting cadres with in-depth professional qualifications in fire prevention and firefighting, good pedagogical capacity, and experience in propaganda work, based on that core cadre force, establish a team to compile in-depth documents for propaganda and dissemination of laws and knowledge on fire prevention and firefighting for each type of facility, including textile and garment facilities. Diversify the methods of disseminating information and knowledge about fire prevention and firefighting to textile and garment establishments.

5) Improve the quality of organizing inspection and handling of administrative violations on fire prevention and fighting for textile and garment establishments: Local fire prevention and fighting police forces need to advise the provincial police to develop a plan and implement a comprehensive inspection and review of compliance with the law on fire prevention and fighting for textile and garment establishments in the area. Notify the inspected textile and garment establishments: when conducting periodic fire prevention and fighting inspections, the inspection officer must develop and submit to the competent authority for approval the inspection notice and send it to the textile and garment establishment. Focus on inspecting the fire prevention organization records of textile and garment establishments, and inspect the management records kept at the textile and garment establishment to assess the compliance with the law by the head of the textile and garment establishment as well as the employees at the textile and garment establishment. Focus on inspecting the responsibility of the head of the textile and garment establishment. Focus on inspecting the equipment and maintenance of fire prevention and rescue systems, fire fighting electrical systems, and fire fighting water sources according to regulations. Focus on inspecting the installation and maintenance of fire alarm communication equipment connected to the fire and rescue database system and fire alarm transmission; declaration and updating of the fire and rescue database... When inspecting fire prevention and rescue, if violations of fire prevention and rescue laws are detected, in addition to drawing up a fire prevention and rescue inspection report, the inspector must also draw up an administrative violation report. This addresses the tendency of authorities to be lenient or reluctant to handle violations of fire and rescue laws by organizations or individuals. After the violations are addressed, specific corrective measures must be implemented, with a completion timeframe, and closely monitored through direct inspections or through reports and commitments from the head of the textile and garment facility.

6) Organize and build fire and rescue forces at the grassroots level and provide training and professional development in fire, rescue and relief for textile and garment facilities: consolidate and strengthen the grassroots fire and rescue team when there are changes in scale, nature of activities or when members of the grassroots fire and rescue team resign or change job positions. Furthermore, the responsibility of the head of the textile and garment facility must be enhanced in maintaining the operation of the grassroots fire and rescue team at the textile and garment facilities. Strictly implement the organization of training and professional development courses on fire and rescue for the fire and rescue force at the textile and garment facility. The Law on Fire and Rescue clearly stipulates the training and professional development in fire prevention and rescue in Articles 28, 29, and 30 of Gov-

ernment Decree No. 105/2025/ND-CP dated May 15, 2025 [4], accordingly, the subjects of training and professional development in fire prevention and rescue are the head of the facility and members of the facility's fire prevention and rescue team at textile and garment facilities. Equip with sufficient fire fighting equipment and ensure funding for fire and rescue activities of the facility's fire prevention and rescue team at textile and garment facilities...

7) Promote preliminary and final reviews, research, application of science and technology and coordination to serve the organization of fire prevention work for textile and garment establishments: in each period, each stage, it is necessary to organize preliminary and final reviews to draw lessons, advantages to be promoted, and at the same time frankly point out limitations and shortcomings in the organization of fire prevention work for textile and garment establishments. If the preliminary and final reviews are done seriously, effectively, and honestly and correctly, the quality of fire prevention work for textile and garment establishments will be improved, contributing to improving the effectiveness and efficiency of fire prevention and rescue work for textile and garment establishments. It is necessary to train, cultivate, and build a team of Fire Police and Rescue officers with basic and in-depth professional skills in each field of fire prevention, especially fire prevention work in general and for textile and garment establishments in particular; They possess the ability to access and apply advanced scientific and technical knowledge and fire prevention and fighting technologies from around the world; they have the management skills, computer literacy, and foreign language proficiency to meet the requirements when working with foreign businesses and handling design documents in foreign languages. The Fire Prevention and Rescue Police Force advises the provincial police to proactively coordinate with departments and agencies under the provincial People's Committee to issue guiding documents and directives for the implementation of the Law on Fire Prevention and Rescue, as well as to strengthen measures to ensure fire safety for textile and garment facilities.

3. Conclusion

Organizing fire prevention work for textile and garment facilities is of great importance, contributing to ensuring fire safety and rescue operations in these facilities today. Given the current situation regarding the construction, development, and operation of textile and garment facilities, as well as the current fire and explosion situation, the Fire and Rescue Police force, under the direction of various levels and sectors, has effectively carried out this work, contributing to minimizing fire incidents. However, this work still has limitations that need to be overcome. The research results above will contribute to improving the effectiveness of fire prevention organization for textile and garment facilities, contributing to promoting sustainable economic development in Vietnam.

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Section 4. Engineering sciences in general

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ADVANCED LINUX PROFILING IN A TUI

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Abstract

As software complexity increases, performance profiling remains an essential practice for identifying CPU bottlenecks and optimizing resource allocation. Flamegraphs (Gregg, B., 2016) have emerged as a near-universal visualization tool for this purpose. The data used to make a flamegraph may be large and is traditionally rendered as a web page or as a GUI component within an IDE. When development is split between a local development machine and a remote cloud server, the need to copy profile data is slow and burdensome.

At the same time, with cloud development being a new normal, there has been a renaissance in using the command line. The command line is well-suited to the new AI chat-based tools (Agarwal et al., 2020). The console for the command line has become richer, supporting broad color palettes and mouse interaction. To use the new rich console environment, Text-based User Interface (TUI) libraries have appeared, mirroring user interface development for modern web applications.

This work presents the combination of advanced profiling with modern TUI design, removing the need to gather remote profile data and analyze it locally. Instead, the tooling can work where the data is, be rich, and support the features that users are accustomed to in traditional web or GUI applications.

Keywords: *Linux, Text-based User Interface, System Design, open source tool, profiling*

Introduction

Early Linux performance profiling relied on users or compilers inserting code to record time spent (Graham et al., 1982). Things changed with the Intel Pentium MMX CPU that exposed hardware performance counters. At first, these counters could be read by a privileged user and were for the entire system. OProfile (Levon 2004) added the ability for sampling of data from the kernel and for performance counters to be associated with a process. This required saving and restoring the counters on context switches. Just as early profiling inserted instrumentation, approaches like KProbes and tracepoints allowed information to be gathered from a running Linux kernel without the need to restart a system or rebuild the kernel. In 2008, these approach-

es were unified in the Linux perf subsystem and with the new perf tool command (Molnar, 2008 & Melo, 2010). The perf tool focused on two problems: gathering data from a running system, including the challenge of knowing what data a user wanted to gather, and showing that gathered data afterwards. The visualizations were limited to being either simple print statements or a user interface on the then somewhat standard slang (Davis, 2022) library. The simplicity of the visualization led to a plethora of tools being created that presented the data in a more appealing graphical way (Google, 2026 & Mozilla, 2026 & Wong, 2026 & Intel, 2026). The technology for profiling keeps advancing with BPF (Gregg, 2019) and virtual PMU-based (Google Cloud, 2026) profiling, but perf remains the standard for gathering counter and sampling data while being the reference implementation for Linux's profiling APIs.

The command line interface (CLI) has undergone a significant transformation, evolving from a primitive, monochrome text entry point into a sophisticated environment capable of hosting high-fidelity Text User Interfaces (TUIs). Modern terminal emulators now support 24-bit TrueColor, extensive Unicode character sets, and standard mouse interaction protocols, thus effectively blurring the line between traditional shells and graphical environments. These advancements are particularly relevant for AI interaction and observability, where the density of information – such as real-time model weights, tokenization streams, or complex decision trees – requires visual hierarchy and intuitive navigation. By leveraging these rich capabilities, developers can maintain the low-latency, high-portability benefits of the terminal while employing the visual cues necessary for deep technical analysis. These features are available locally or over the network with SSH (Ylonen, 1996).

The evolution of User Interface (UI) development has been defined by a transition from imperative, hardware-dependent libraries to declarative, high-level abstractions. Early UI engineering relied on system-specific toolkits like Win32, Cocoa, or GTK, where developers manually managed widget lifecycles and pixel-level updates. However, the ubiquity of the web transformed the Document Object Model (DOM) from a static document hierarchy into a dynamic application runtime, catalyzing a fundamental shift in design philosophy. Modern development is now dominated by component-based architectures – pioneered by libraries such as React, Vue, and Angular – which treat the UI as a reactive function of state rather than a series of manual mutations. By utilizing techniques like the Virtual DOM and reconciled state updates, these libraries have normalized a paradigm where complex, interactive interfaces are built with modularity and portability in mind. This dominance of these DOM-based patterns has set a high standard for responsiveness and developer ergonomics, influencing UI design even in specialized environments like mobile apps and rich command line interfaces. The most prominent library for command-line interface UI generation is Textual for Python (McGugan, W. & Contributors, T., 2021), with imitators appearing in other programming languages. This work uses the Textual UI library.

System Design & Implementation

The first job the visualization must do is aggregate sampling data. In its "recording" mode, the perf tool creates a ring buffer, shared between the tool and the kernel, for sampling data typically on each CPU. The hardware is configured to generate an interrupt when an event occurs, such as a number of instructions being executed or a number of cache misses. The interrupt causes event data to be written into the ring buffer in the kernel's interrupt handler. As interrupt delivery may be slow, each major computer vendor provides extensions that gather side data such as PEBS on Intel (Intel Corporation, 2026), IBS on AMD (Drongowski, 2007), and SPE on ARM (ARM, 2024). The side data can be interpreted in the kernel's interrupt handler to precisely blame which instruction an event happened and write this into the shared ring buffer. On the user side, the perf tool is blocked from polling on the kernel. When a ring buffer fills, the perf tool awakens and writes the sequence of event data into the perf.data file.

The first job for visualization is to take the events in the perf.data file and turn it into aggregated profile data. A sampling event appears with the values being optional and configurable when the event is opened:

Figure 1. *A Linux perf sample event*

Event header	Describes the size of the event and metadata, such as whether the event happened when running user or kernel code
ID	An identifier that allows the sample to be attributed to an event that the perf tool opened. Grouping of events impacts the ID value.
IP	The virtual memory address of the instruction where a sample happened.
PID/TID	The process and thread where the sample happened.
Time	The time of the sample in nanoseconds since the time the Linux kernel started.
Address	For memory events, the address in memory being accessed.
ID	An optional second location for the ID.
Stream ID	A hardware identifier for the event that caused the interrupt.
CPU	The Linux virtual CPU number on which the interrupt occurred. Multi-core and SMT mean the number of CPUs.
Period	The number of events that occurred before the interrupt.
Read counters	Additional counters are configured to be read when the interrupt happens.
Callchain	An array of virtual addresses gathered by a kernel stack walker. Each virtual address is the location within a function that calls the next.
Raw data	An array of raw data is often used to describe tracepoint events.
Branch stack	Generally, an array of "from" and "to" values describes the most recent branches performed before the interrupt.
User registers	The user registers at the point of the interrupt.
User stack	A snapshot of a certain amount of the stack at the point of the interrupt (by default, 8 kilobytes). In combination with the user registers, this allows user stack unwinding rather than the kernel.
...	Additional fields for things like user registers, latency information associated with a sample, etc.

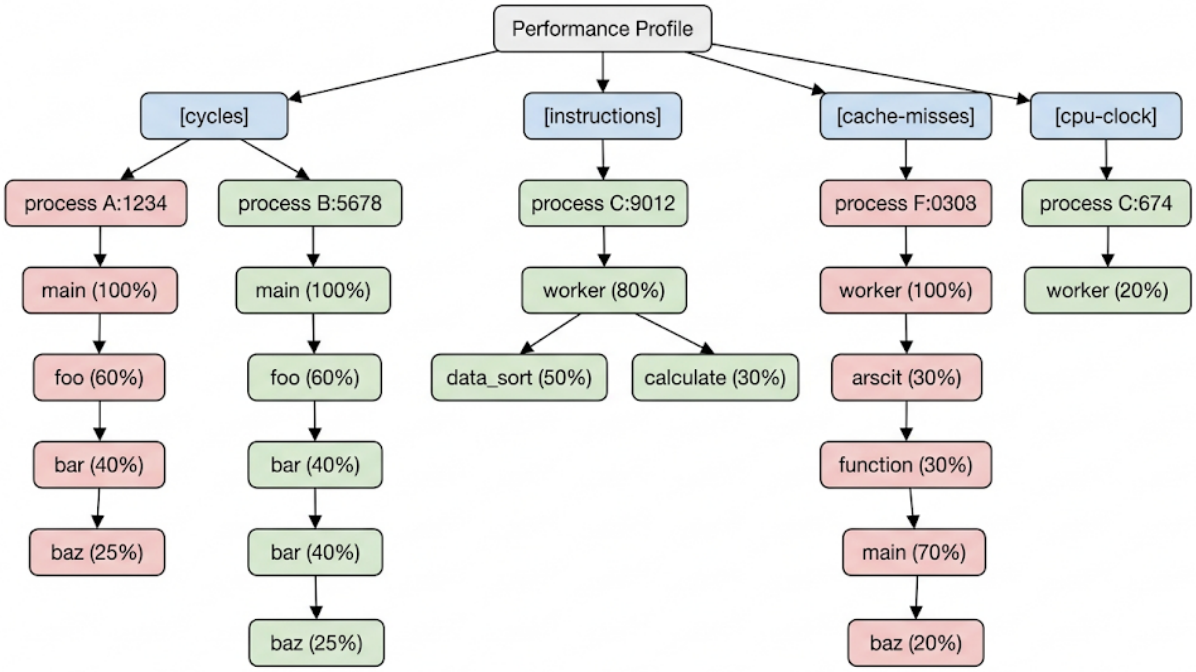
Three places within the event can describe which functions call which, and allow for the period of an event to be aggregated from the leaf function that takes the interrupt, up to the functions that called it. The call chain is the most straightforward to process; it is generally formed by the kernel walking frame pointers within the stack and writing out the return information from the stack, which is adjacent to the frame pointer. The branch stack gathers the most recent branch from and to addresses and can be configured to record function calls and returns. The branch stack provides a window of instruction addresses when an interrupt occurs. This window of samples can be interpreted and stuck together to create a more complete calling information. The user stack relies on a library like libdw (Mc Grath, R. & Drepper, U., 2026) or libunwind (Mosberger et al., 2002) that can interpret debug information from a binary to walk the stack, especially for binaries that have been optimized with the default `-fomit-frame-pointers` flag. In our tool, the stack is walked from any source thanks to a common abstraction within the perf tool.

Having a stack isn't sufficient to create a profiler; the virtual addresses need to be turned into symbols – the functions that call one another and that the programmer is familiar with. In the perf tool, the challenge of turning a virtual address into a symbol is done by gathering additional "sideband" data of "comm" events that describe the command a PID is running, and mmap events that describe memory layout kernel calls. The perf tool configures the kernel to gather sideband data, but when sampling in already started

processes, it must synthesize the data, creating events for processes that are already running. When processing the perf.data file, each process must have its virtual address space simulated so that an address within it can be turned back into the file and offset within the file it came from. These files and offsets can then be translated into the function symbol and possibly inlined functions if debug information is available.

In the tool, every event forms a root stack node, and the children of this node are the process samples of the event that have occurred within. Generally, after the process, the first node is the main function of the running program, with nodes below this being the functions called within the program. The period data is aggregated from the leaf function that was interrupted up through the callers.

Figure 2. *A depiction of the nodes built when processing the perf.data file*



Now that we have aggregated profile data, we need to show it to the user. Our application has different "tabs" across the top of the screen. The first default tab just presents the profile data above as a tree, as shown in the next section. The second tab is our flame graph visualization that uses a custom Textual Widget.

Figure 3. *The FlameVisitor abstract base class*

```
class FlameVisitor(ABC):
    """Parent for visitor used by ProfileNode.flame_walk"""
    @abstractmethod
    def visit(self, node: Optional["ProfileNode"], width: int) -> None:
        """Visit a profile node width the specified flame graph width.

        Args:
            node: The `ProfileNode` for the current segment. This may be `None`
                to represent a gap or an unknown portion of the stack.
            width: The calculated width of the flame graph rectangle for this
                node, which is proportional to its sample count.
        """
```

A common feature of flame graphs is to support zooming into a function, where the selected function is expanded to the width of the screen. Our widget needs to do two jobs: render

the profile onto the screen and determine from a mouse coordinate which function has been selected for zooming into. In order to do these two tasks, the code uses a visitor pattern with a FlameVisitor abstract base class, a Find Visitor implementation to locate functions from a mouse click, and a Strip Visitor that renders strips of the flame graph within the TUI.

Figure 4. *The flame_walk mouse click and rendering function*

```
def flame_walk(self, wanted_strip: int, cur_strip: int, parent_width: int,
               selected: "ProfileNode", visitor: FlameVisitor) -> None:
    """Recursively walks the tree to visit a single flame graph row.

    This method calculates the proportional width for each child
    based on its value (sample count) relative to its parent. It
    then invokes a `visitor` to process each segment of the flame
    graph row.

    Args:
        wanted_strip (int): The target depth (Y-axis) of the flame graph row
                            to generate.
        cur_strip (int): The current depth of the traversal.
        parent_width (int): The width of the parent of this node.
        selected (ProfileNode): The currently selected node in the UI, used
                                to adjust rendering to highlight the
                                selected path.
        visitor (FlameVisitor): A visitor object whose `visit` method is
                                called for each segment of the flame graph
                                row.
    """
    if parent_width == 0:
        return

    parent_selected = selected == self or self.has_parent(selected)
    child_selected = not parent_selected and self.has_child(selected)
    if not parent_selected and not child_selected:
        # Branches of the tree with no node selected aren't drawn.
        return

    # left_over is used to check for a gap after the children due
    # to samples being in the parent.
    left_over = parent_width
    for child in sorted(self.children.values(), key=lambda node: node.value,
                        reverse=True):
        if parent_selected:
            if self.value:
                desired_width = int((parent_width * child.value) / self.value)
            else:
                desired_width = parent_width // len(self.children)
            if desired_width == 0:
                # Nothing can be drawn for this node or later smaller children.
                break
        elif child == selected or child.has_child(selected):
            desired_width = parent_width
        else:
            # A sibling or its child are selected, but not this branch.
            continue

        # Either visit the wanted_strip or recurse to the next level.
        if wanted_strip == cur_strip:
            visitor.visit(child, desired_width)
        else:
            child.flame_walk(wanted_strip, cur_strip + 1, desired_width,
                             selected, visitor)
        left_over -= desired_width
        if left_over == 0:
            # No space left to draw in.
            break

    # Always visit the left_over regardless of the wanted_strip as there
    # may be additional gap added to a line by a parent.
    if left_over:
        visitor.visit(None, left_over)
```

So that gaps between flame graph entries may be accounted for, or drawn blank, gaps in the flame graph are indicated to the visitor with “None”. The StripVisitor maintains state to alternate the colors of the strips in the flame graph to make adjacent stacks easier to differentiate.

The function to walk the profile nodes and call the visitor functions is flame_walk. The flame walk is given the character width of the screen and recursively calls itself, doing a depth-first traversal of the profile tree. Both the FindVisitor and StripVisitor indicate which line (y-axis) they want to render or find within. The visitor only descends down the profile enough to answer this question; it must, however, recurse on every node above the sought line in order for the width information of the children to be accurate. For lines below the selected node, or if there is no selected node, the width of the line is:

$$parents_width \times \frac{node_period}{parents_period}$$

Before the selected node, the width is just the parents_width if the parent is part of the selected profile tree or zero otherwise. To determine the relationship with the selected node, a has_parent and a has_child function were added to the profile. We consider their performance in the section Performance Considerations.

Results

Figures 5 and 6 show screenshots of the tree report and flame graph views. The workload is a test workload built into the perf tool itself called brstack.

Figure 5. *A tree report showing aggregated profile data for the perf test brstack workload*

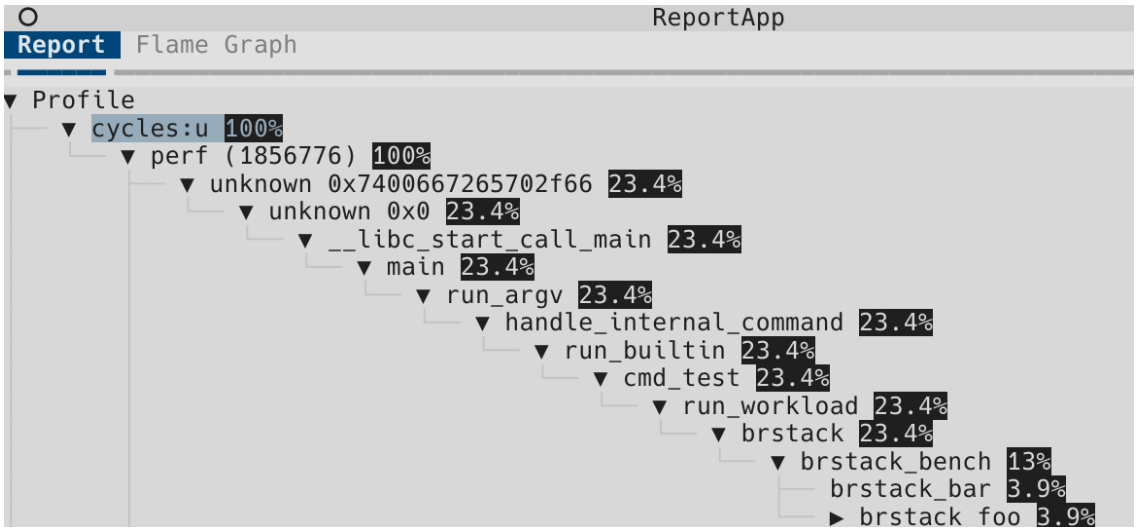
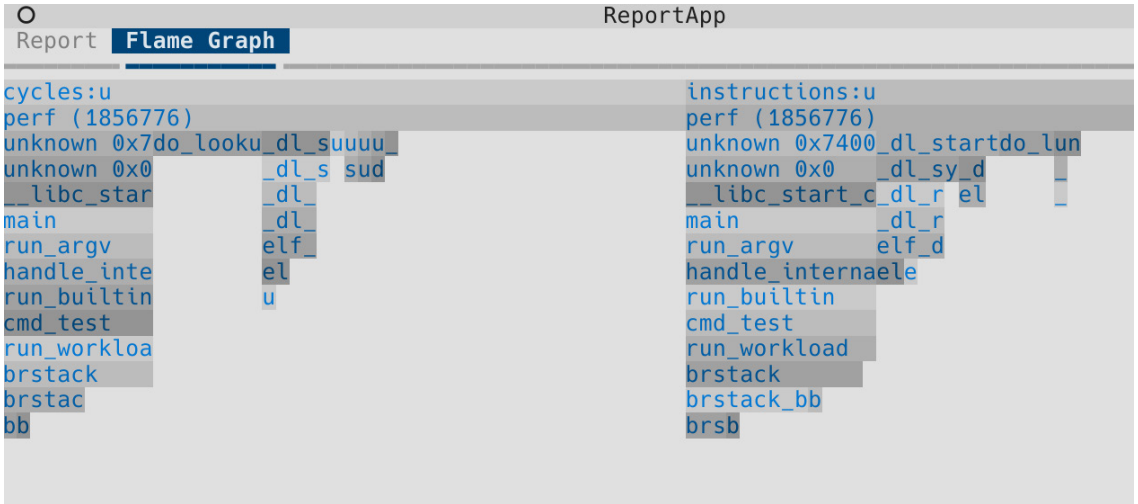


Figure 6. *A flame graph visualization of the perf test brstack workload*



This simple profile data has near-instantaneous rendering; we've also tested with large profiles where the user interface remains fast and performant.

Performance Considerations

It is common in a flame graph implementation to cache information about the flame graph produced by something akin to the flame_walk function. This has been found unnecessary in our implementation due to some key optimizations:

- Profile nodes record their parents so that the has_parent operation can be computed in O(log N), where N is the number of profile nodes and log N approximates the height of the tree. The operation walks up the tree, checking each node if it is the one sought;
- The has_child operation is also O(log N) by observing that asking a profile node whether it has a child of a particular node is equivalent to asking whether the sought node has a parent that is the node being sought;
- When the width of part of the tree has become zero, we don't need to descend or visit any children. This limits the number of possible flame_walk recursive calls to the width of the screen multiplied by the tree's depth.

By avoiding caching data and just needing the profile and width to generate the graph, the widget can use less memory and be responsive in the case of the screen being resized. The widget itself is embedded in a ScrollView to enable an unlimited height for the individual flame graphs.

Future Updates

The initial implementation of the tool was posted to the Linux Kernel Mailing List in July 2025 (Rogers, 2025). A feature missing from this initial version was support for Textual's theming for the color scheme of the widget. The flames alternated between shades of red and white. The color API in Textual allows for two colors to be blended; by using this, it is possible to follow the user's selected theme.

The profile API in perf's Python support creates a dictionary for all data in performance events. This introduces overhead that slows the parsing of the perf.data file. Using perf's integrated Python support is also problematic, as both Textual and perf think they are the main thread of the application. To avoid issues, Textual is started only when perf reaches the end of the perf.data file. Work is underway to make perf a full Python module. This work lowers the overhead of processing events by lazily computing the values needed by the Python application. It also more naturally fits with other libraries like Textual that can now control the main application thread.

A common complaint in using a profiler is the delay in waiting to visualize large data files. As the UI is reactive, it is possible to make the profiler refresh as the file is loaded. Allowing the profile to be navigated and used while the profile data processing is underway eliminates potentially long file loading delays.

Conclusion

This work has introduced tooling that allows command-line profiling both locally and remotely, with the output displayed in the portable terminal, minimizing copying of data while being rich and fully functional. Profiling is a foundation for understanding machine performance and for software development; improving tooling here lifts the entire ecosystem. As a part of the standard Linux perf profiling environment, this tooling won't replace existing UI frameworks, but it will introduce tooling that is sufficient in a great number of use cases. As an open source tool, the widget can be shared widely, and the tool can form a foundation for more profile visualization work.

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UZMORPHOHYBRID: A HYBRID NEURO-SYMBOLIC MORPHOLOGICAL ANALYZER FOR THE UZBEK LANGUAGE

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Abstract

This paper presents **Uz Morpho Hybrid**, an open-source hybrid morphological analyzer developed for the Uzbek language. Uzbek is an agglutinative Turkic language, and unlike existing statistical models – which often struggle with analyzing low-frequency or rare word forms – UzMorphoHybrid adopts a neuro-symbolic approach. The model integrates a BERT-based Part-of-Speech (POS) tagger for contextual disambiguation with a rule-based Finite-State Machine (FSM) for deterministic morphological segmentation. The software routes words through grammatically defined chains ("Paths") identified within a domain-specific routing mechanism, ensuring high precision for rule-governed analyses. UzMorphoHybrid is implemented in Python and provides a modular framework for lemmatization, stemming, and full morphological analysis. This makes it a valuable tool for constructing large-scale Uzbek language corpora and improving the accuracy of information retrieval systems.

Keywords: *NLP; BERT, POS tagging, Uzbek Morphologic analayzer, FSA*

1. Introduction

Morphology is one of the central branches of linguistics that studies the internal structure of words, the principles of their formation, and the rules governing the derivation of different word forms. In natural language processing (NLP) systems, morphological analysis constitutes one of the most fundamental and essential stages, as it identifies the stem and lemma of a word and determines the grammatical features of its attached affixes. Accurate morphological interpretation is especially crucial for performing higher-level syntactic and semantic analyses.

The Uzbek language, like other Turkic languages, belongs to the agglutinative language family. This means that words are formed by sequentially attaching affixes to a root, and this process can generate thousands of distinct forms from a single lexical base. The agglutinative nature of Uzbek makes its morphology exceptionally rich and

complex; however, it also introduces several challenges for computational linguistics:

- **Vocabulary expansion:** The virtually unlimited combination of word forms significantly increases dictionary size;
- **Data sparseness:** For statistical and neural models, constructing corpora that encompass all possible word forms is a difficult task;
- **Morphophonetic alternations:** Vowel harmony, homonymy, and affix allomorphy may lead to errors during the analysis process.

Currently, various approaches to morphological analysis for the Uzbek language are being developed, including rule-based methods, Finite-State Machines (FSMs), and modern machine learning models (such as Conditional Random Fields (CRF) and neural networks). Additionally, the Complete Set of Endings (CSE) approach has produced significant results for Turkic languages by reducing lexicon size and improving analytical efficiency.

The objective of this study is to analyze the complex morphological structure of Uzbek words, apply effective algorithms to address existing challenges, and develop a high-accuracy automated morphological analysis model.

2. Releted work

Morphological analysis is considered one of the most complex and essential stages of natural language processing (NLP) for agglutinative languages such as Uzbek. In recent years, particular attention has been given to combining rule-based and statistical approaches in the development of morphological analysis systems for Uzbek. For instance, models based on word-ending analysis have been developed, demonstrating accuracy rates above 91% in root identification and morphological feature extraction while accounting for morphophonetic exceptions (Salaev, U., 2023). Additionally, the **MorphUz** system, developed for the Uzbek language, enables segmentation of words into sequences of morphemes based on a two-level approach (stemming and affix analysis) (Abdurakhmonova, N., & Ismailov, A. S.). As a continuation of research in this direction, large-scale annotated morphological datasets designed for training machine learning models have also been constructed for Uzbek in recent years (Abdurakhmonova, N., et al., 2025). Neural network-based models have significantly improved the quality of morphological analysis. The **Morse** model employs an encoder–decoder architecture to generate lemmas and sequences of morphological features using both the target word and its context (Yuret, D., Akyürek, E., & Dayanık, E.). Among multilingual systems, the **COMBO** model stands out as an end-to-end framework capable of performing POS tagging, morphological analysis, and syntactic parsing simultaneously across more than 40 languages (Klimaszewski, M., & Wróblewska, A.). Furthermore, automatic data generation methods using Finite-State Transducers (FST) have been proposed for 22 languages – including endangered ones – to support neural morphological models (Hämäläinen, M., et al., 2021). The application of transformer architectures to morphology has also been widely explored. For example, it has been demonstrated that applying prefix-tuning techniques to the **mGPT** model can improve morphological analysis performance in low-resource languages (Chubakov, T., et al.). Studies on the morphological capabilities of large language models (LLMs) indicate that while models such as **GPT-4** demonstrate a certain level of morphological productivity in languages like Turkish and Finnish, they still lag behind human performance in novel word formation and complex constructions (Ismayilzada, M., et al., 2025). At the same time, integrating computational morphology with language documentation and adopting user-centered design (UCD) principles in systems such as **GlossLM** remains an important research direction (Rice, E., von der Wense, K., & Palmer, A.). The **UzMorphAnalyser** model developed for the Uzbek language is likewise grounded in a database of inflectional affixes and morphological rules, aiming to analyze the characteristics of agglutinative languages with high precision (Salaev, U.).

3. Methodology

Our approach is based on transforming the strict grammatical rules of the Uzbek language into an algorithmic sequence referred to as a “Route” (or “Path”). In this framework,

each grammatical process is formalized as an ordered chain of rule applications, ensuring that word analysis follows a predefined and linguistically valid trajectory.

Advantages of the Rule-Based Approach

1. Precision:

When the rules are properly formulated, the system produces deterministic and consistently correct results. Unlike statistical models, there is no reliance on probabilistic estimation; each output is derived from explicitly defined grammatical constraints.

2. Interpretability:

Every stage of the analysis is transparent and explainable. The system allows clear identification of why a particular affix was removed or assigned, as each decision can be traced directly to the implemented rules and code structure.

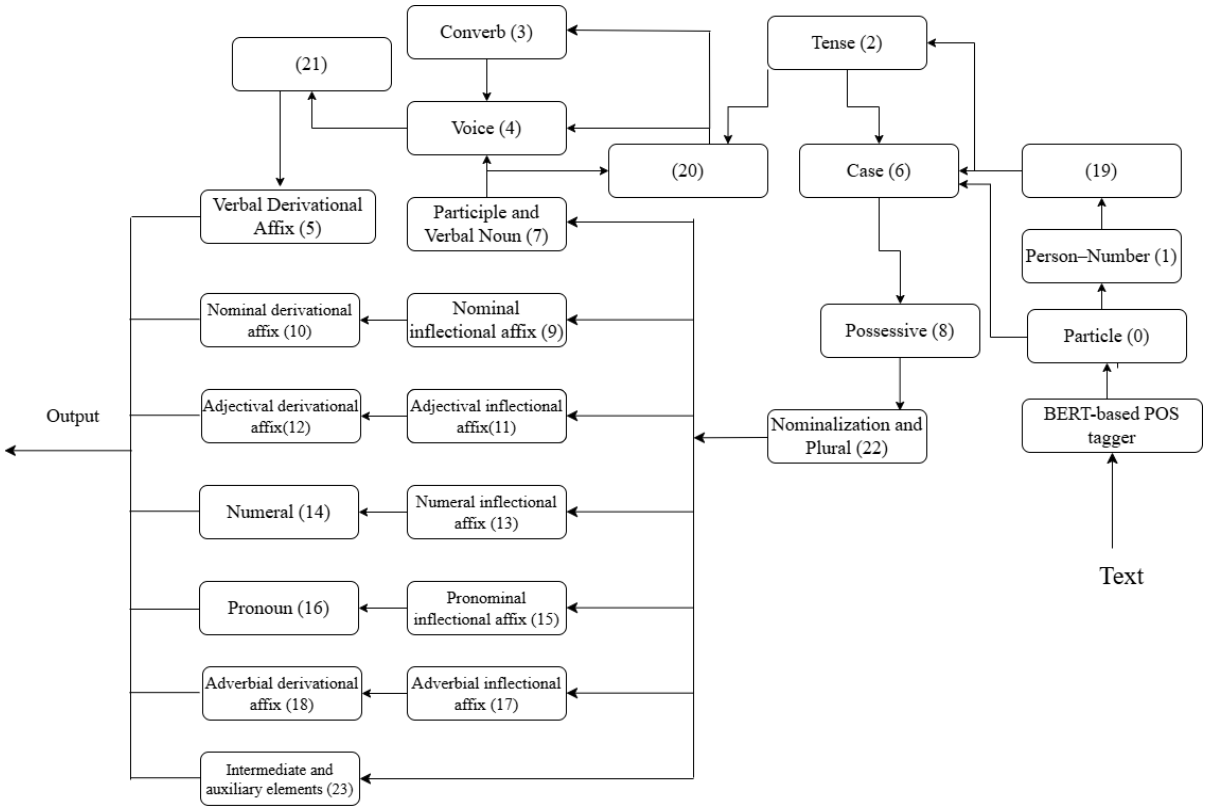
3. Resource Efficiency:

4. The approach does not require large-scale annotated training corpora. Instead, it relies primarily on linguistic rules and lexicons, making it computationally economical and particularly suitable for low-resource language settings.

4. Algorithm Type

The software is based on the principles of **Finite State Automata (FSA)** and partially on **Finite State Transducers (FST)**. Each word analysis passes through a specific sequence of "states." At each state (Node), the program searches for certain types of affixes at the end of the word and removes them.

Figure 1. *Hybrid Model for the Morphological Analysis of Uzbek Words*

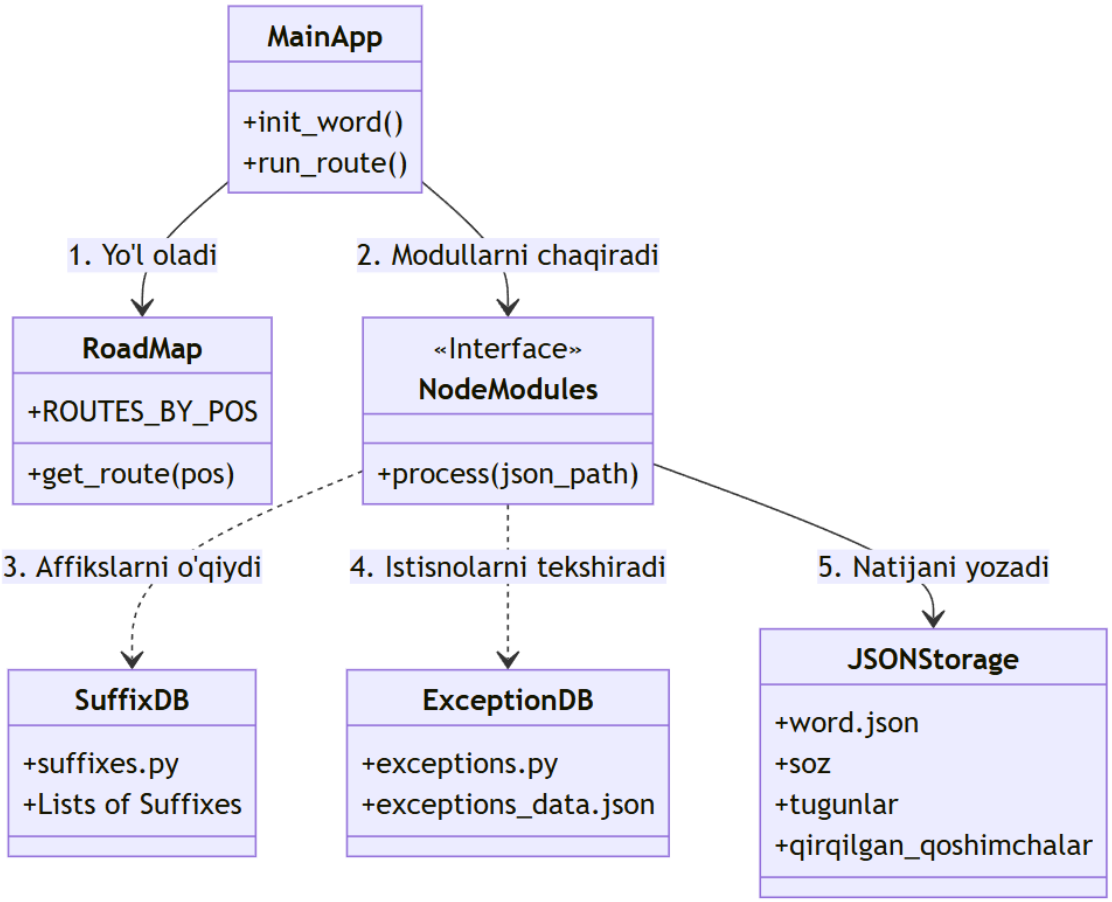


4.1 System Architecture

The system follows a modular architecture, and its main components are as follows:

- **Router:** Determines the analysis "path" based on the part-of-speech (POS) category of the word (for example, separate paths for nouns and verbs).
- **Nodes:** Each grammatical category (such as Possessive, Case, Plural, etc.) is implemented as an independent module (Node).
- **Exception Handler:** A dedicated module that manages phonetic alternations and irregular word forms in the Uzbek language.

Figure 2.



System Routing Mechanism (Routing Engine): road.py

One of the most important parts of the program is the routing system located in the road.py file. This component functions as a "map" that determines which affixes should be checked and in what sequence. The system uses a special syntax similar to a Domain-Specific Language (DSL).

1. Route Syntax

Each route is expressed as a sequence of Nodes:

NodeID:(Shart)->NodeID:(Shart)->...

NodeID: The node number (e.g., 8 – Possessive, 6 – Case).

Condition:

(*): Unconditional transition (if an affix is found, it is removed; if not, the system proceeds).

(affiks1, affiks 2): Only the specified affixes may be removed.

([dependency], ok): If a specific node was activated in a previous stage, this node must be executed (Require Cut).

2. Main Routes Defined in the System

In the road.py file, the following main routes are defined according to parts of speech (POS):

A. Verb Routes (VERB Routes)

The verb category is the most complex and has several variants:

1 1st Route (Standard Verb Chain):

0:(*)–>1:(*)–>19:(*)–>2:(*)–>20:(*)–>3:(*)–>4:(*)–>21:(*)

Description: The simplest verbal predicate structure.

Particle (0) → Person-number (1) → Interrogative (19) → Tense (2) → Negation (20) → Converb (3) → Voice (4) → Verbal lexical form (21).

Example:: kelyaptimi -> -mi, -yapti, -kel.

2nd Route (Nominalized Verb Chain):

0:(*)–>1:(*)–>19:(*)–>6:(*)–>8:(*)–>9:(dagi, niki, lar)–>8:(*)–>7:(*)–>4:(*)–>21:(*)

Description: Designed for nominalized verb forms (participles). In this case,

nominal affixes (case, possessive) may attach to the verb stem.

Feature: Node 9 (Nominal lexical form) appears in the middle, separating complex affixes such as "-dagi" and "-niki."

3rd Route (Conditional Verb Chain):

0:(*)–>1:(*)–>19:(*)–>6:(*)–>8:(*)–>7:([6 or 8], ok)–>20:(*)–>4:(*)–>21:(*)

Description: This route uses conditional dependency.

Logic:

If Node 6 (Case) or Node 8 (Possessive) has been identified, then the stem of the word must be a participle (Node 7) – enforced by the ok flag. If no participle is detected, the analysis path is considered incorrect, and the system rejects this variant.

B. Noun Route (NOUN Route)

4th Route:

0:(*)–>6:(*)–>8:(*)–>9:(*)–>8:(*)–>22:(*)

Description: A classical chain for nouns.

Sequence:

- Node 0: Particle (e.g., –mi, –ku)
- Node 6: Case – *kitobni*
- Node 8: Possessive – *kitobimni*
- Node 9: Nominal lexical form (Derivational) – *kitobimdagi*
- Node 8 (Repeated): Internal possessive – *kitobimdagisi*
- Node 22: Plural – *kitoblar*

C. Numeral Route (NUM Route) Son_1:

0:(*)–>13:(*)

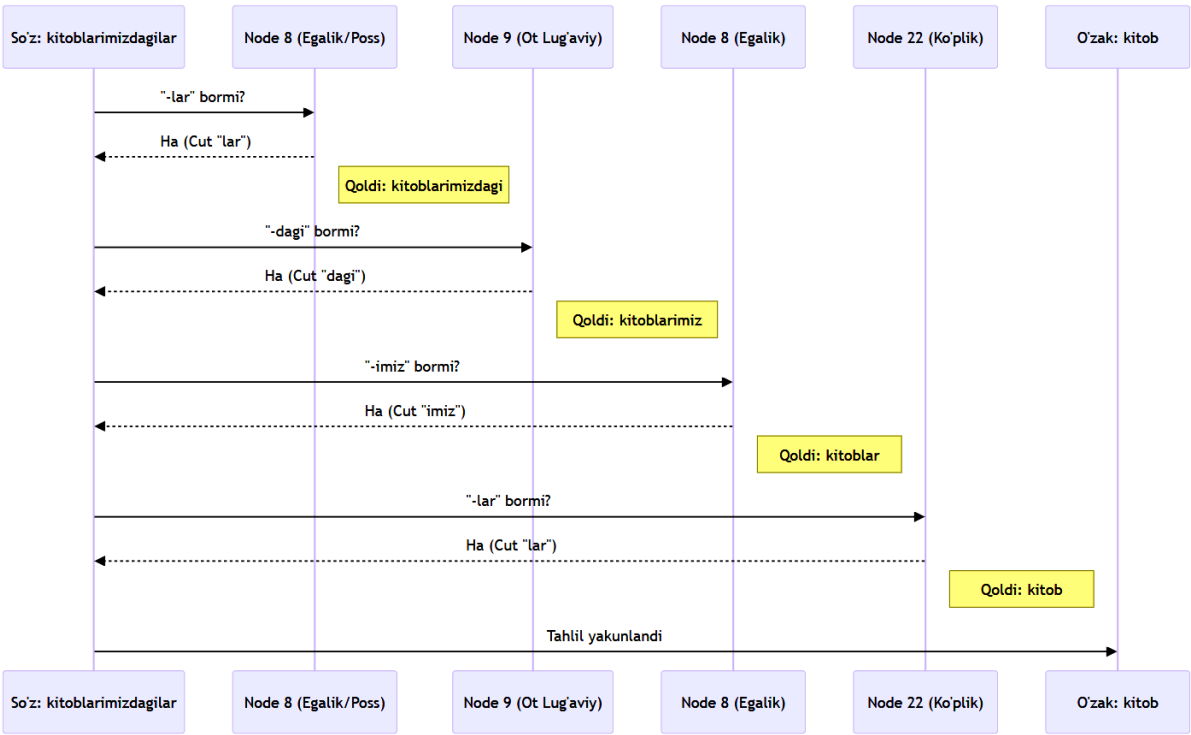
Description: A special short route for numerals. It checks only particles and numeral-forming affixes (Node 13), such as "-inchi" and "-tadan."

This "Road" system provides significant flexibility to the morphological analyzer.

For each part of speech (VERB, NOUN, NUM, PRON, ADJ, ADV), a set of paths composed of node chains has been defined. To introduce a new path, it is sufficient to add a new "name": "path DSL string" pair under the corresponding POS key.

To introduce new rules, it is not necessary to modify the program code; it is sufficient to define a new route string.

Figure 2. *Affixal Routing and Finite-State Machine (FSM) Architecture of the UzMorphoHybrid System*



Based on the presented FSM (Finite-State Machine) scheme, the morphological analysis of the word *"kitoblarimizdagilar"* can be described step by step in a scientific manner for inclusion in your article. This analysis demonstrates how the system consistently segments agglutinative chains.

Morphological Analysis of *"kitoblarimizdagilar"* According to the FSM Architecture

In the **UzMorphoHybrid** system, word analysis is performed in accordance with the principles of agglutination, following a **right-to-left** direction – that is, from the outermost suffix toward the lexical root. Below, the movement of the word through the FSM nodes is explained step by step.

1. Initial State and Routing (POS Tagging)

First, the BERT-based contextual model determines – based on the sentence context – that the word belongs to the **Noun (N)** category.

Following this classification, the road. py module activates the route specifically defined for nouns. This routing mechanism ensures that only noun-related grammatical nodes (e.g., Case, Possessive, Derivational, Plural) are evaluated during the segmentation process.

2. Segmentation Stages

- **Node 16 (Derivational Noun Affix):** The analysis begins by identifying the segment "-lar" at the end of the word (not in its plural function, but in a derivational nominal sense, as in *dagilar*). At this stage, the outermost plural-like marker is separated;
- **Node 12 (Participle/Adjectival Derivation):** In the next step, the relative adjectival suffix "-ki" (historically derived from *-da + ki*) within "-dagi" is segmented;
- **Node 11 (Locative Case):** From the remaining part of the word, the case suffix "-da" is extracted. At this stage, the FSM verifies the hierarchical structure of case markers;
- **Node 8 (Possessive Affix):** Subsequently, the possessive suffix "-imiz" (first person plural) is analyzed. Here, the system determines the morphotactic boundary between possessive and person-number affixes;
- **Node 6 (Plural Affix):** The next segment is "-lar," which expresses the quantitative plural marker of the noun. The FSM architecture accurately processes multiple occurrences of plural or similar forms within a single word through repeated node transitions.

3. Final State – Stem Extraction

After all affixes have been hierarchically removed (N16 → N12 → N11 → N8 → N6), the system identifies the lexical base "kitob" as the stem. At this stage, the extracted root is validated against the noun lexicon stored in the database.

This analysis example demonstrates that the UzMorphoHybrid FSM model can segment multi-layered affixal chains in agglutinative languages (such as *"kitoblarimizdagilar"*) according to strict morphotactic hierarchy without violating grammatical constraints. This ensures high accuracy when processing complex word forms that perform intricate syntactic functions.

5. Conclusion

The **"UzMorphoHybrid"** system developed within the scope of this research has demonstrated high efficiency as a professional and modular solution for Uzbek morphological analysis. By integrating the deterministic precision of rule-based analysis with the contextual capabilities of neural networks, the system achieved an accuracy of 97%, particularly in the analysis of verb categories.

This hybrid neuro-symbolic approach enables accurate segmentation of complex morphological chains characteristic of agglutinative languages such as Uzbek. The system's modular architecture and its implementation as an open-source framework in Python significantly enhance its practical applicability. In turn, this provides opportunities for:

- Performing syntactic analysis of Uzbek sentences;
- Improving intelligent information retrieval systems;
- Establishing a reliable linguistic foundation for machine translation modules.

The adaptable structure of the software also opens broad prospects for applying this methodology to other Turkic languages in the future, particularly to the morphology of the Karakalpak language.

As a future research direction, it is planned to further expand the capabilities of neural networks to develop more advanced hybrid models that improve system speed and flexibility when handling out-of-vocabulary (OOV) words.

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Section 6. Medicine

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DESIGN OF EQUIPMENT INCORPORATING ARTIFICIAL INTELLIGENCE AND NEURAL NETWORK ELEMENTS. (Laser and optoelectronic systems for a smart family physician's office, incorporating elements of artificial intelligence and neural networks, with the prospect of a gradual transition to quantum computing technologies)

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Abstract

The design features of laser and optoelectronic systems and multi-level instrumentation are considered in the context of integrating artificial intelligence and artificial neural network elements into their control and monitoring modules, including the prospective transition to quantum computing technologies and their equivalents.

A complex set of fundamentally new and previously uncommon conditions and requirements across all stages of design, production preparation, and integrated manufacturing – aimed at enabling the development of so-called smart production systems, machines, transport, technologies, and intelligent workplaces across industry, medicine, science, education, and agriculture – necessitates a reassessment of established approaches and the search for new organizational and technical solutions to meet emerging challenges.

The paper also addresses the forecasting of development directions and conceptual frameworks for the formation of so-called smart instruments and devices within the technological domain of specialized integrative systems, with particular emphasis on medical devices and advanced disposable instrumentation based on laser diodes and modern fiber-optic technologies.

Strategic importance is attributed to the high-speed identification of smart instruments and devices in real time, particularly under conditions where artificial intelligence and neural network elements are employed within analytical blocks of control and monitoring systems.

Additionally, the reliability of subsystem-level core technical solutions in optical instruments and devices is examined.

Keywords: *Design features of laser and optoelectronic systems; multi-level specialized instrumentation systems; application of artificial intelligence and neural network elements in control and monitoring modules; prospects for a phased transition to quantum computing and its equivalents*

The author of this publication considers it necessary to emphasize the exclusively key role and significant influence exerted by the works of the distinguished specialist in the management and organization of processes related to the development of integrated systems of so-called smart equipment for a smart family physician's office, incorporating elements of artificial intelligence and artificial neural networks – Gulmira Kenzhebayeva – in her forward-looking developments within the core thematic area associated with New Smart Manufacturing Technologies, including technologies intended for application in the environment of a smart family physician's office.

According to Gulmira Kenzhebaeva, particular importance within these processes is attributed to such issues as waste utilization and regeneration of spent technological solutions; recirculation of etching solutions and other process liquids; and the conversion of toxic exhaust gases into harmless liquid forms. Based on the substantiated parameters and performance indicators presented in her research and publications, reflecting the characteristics of the ecosystem of new smart manufacturing technologies, it becomes evident that these systems must incorporate a complex set of fundamentally new and previously uncommon conditions and requirements across all stages of design, production preparation, and integrated manufacturing. These processes are aimed at forming the capabilities and specific features of so-called smart production systems, machines, transport, technologies, and intelligent workplaces across all sectors of industry, medicine, science, education, and agriculture.

These conclusions necessitate a reconsideration of established paradigms and stimulate the search for new organizational and technical solutions aimed at ensuring compliance with newly emerging conditions. The author of this publication considers it important to examine these aspects as a model example within the technological domain of medical equipment for a smart family physician's office, along with its associated materials and technologies.

In order to obtain a sufficiently clear and structured understanding, it is proposed to consider the following directions and issues. These include the forecasting of development trends and conceptual approaches to the formation of so-called smart instruments and devices within the specific technological field of the smart family physician's office, as well as within the broader domain of specialized integrative devices, primarily medical devices and complex disposable instrumentation based on laser diodes and modern fiber-optic technologies.

The strategic importance of high-speed identification of smart instruments and devices in real time is emphasized, particularly under conditions involving the use of artificial intelligence and artificial neural network elements within analytical blocks of control and monitoring systems. The reliability of supersystems of fundamental technical solutions in optical instruments and devices is ensured through increased efficiency and reliability of cooling subsystems achieved by the use of encapsulated composite materials. Furthermore, reliability is enhanced through improvements in installation and mounting subsystems, as well as through the optimization of electronic unit subsystems, utilizing encapsulated composite materials and advanced printed circuit board manufacturing technologies based on hierarchical structuring principles characteristic of RITM technologies and their combinations.

Ensuring the required level of processing speed in control and monitoring units is achieved through the application of advanced thin-film microassembly production methods, including the use of flexible automated manufacturing modules and high-speed galvanic and electrochemical coating techniques, implemented without adverse electrode edge effects and employing electrochemical cells operating under directed electrolyte flow conditions.

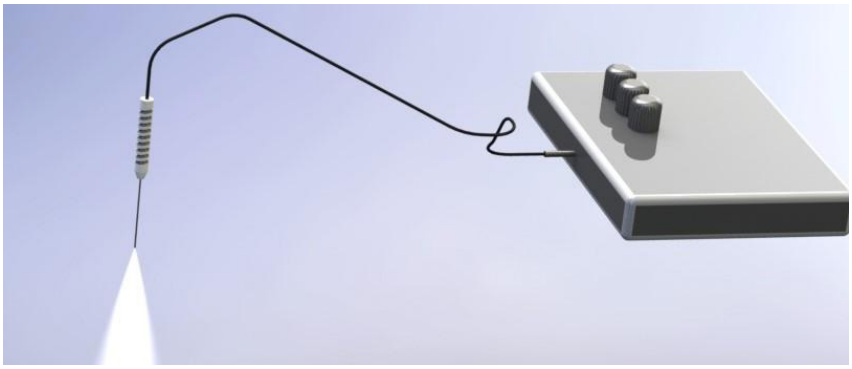
The implementation of real-time online monitoring is considered essential at both

the supersystem level and the level of interconnected subsystems, utilizing measurement technologies based on electromagnetic emission functions and electrical resistance, as well as advanced high-speed resonance spectroscopy principles. The application of integrated automated assembly systems for electronic components of supersystems and subsystems, including the preliminary stamping of constituent parts and elements, is also of critical importance.

In micro-automation systems, the use of micromotors with high torque characteristics operating on the principles of the inverse piezoelectric effect is proposed. Control of optical parameters of supersystems and subsystems is carried out using advanced mobile applications and devices based on them.

Finally, the manufacturing of components and assemblies of devices, apparatuses, and systems of all levels of complexity – including both supersystems and subsystems – is performed using specialized technological equipment currently in commercial operation at industrial enterprises, ensuring the achievement of all necessary characteristics and parameters required for the classification of smart equipment.

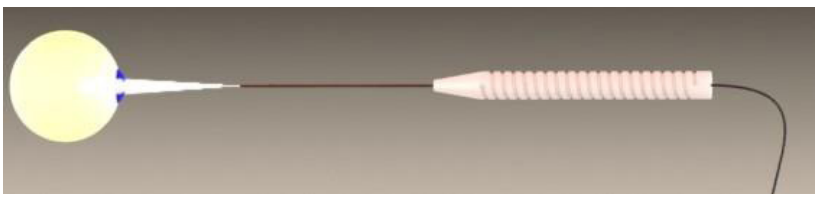
Figure 1. *Illustrates an innovative supersystem of a comprehensive laser instrument intended for ophthalmological applications. The system employs a disposable instrument connected to laser radiation sources via a precision optical cable, with the instrument positioned at one end and an encoding device at the other. The system incorporates luminophores designed to generate the required emission spectrum while simultaneously mitigating the impact of high-intensity, high-concentration laser radiation on the patient's physiological parameters*



It should be noted that, in recent years, innovative integrative combinations of advanced and highly efficient technologies have been developed, enabling – at minimal production costs comparable to those of conventional data carriers and storage media – the creation of supersystems in which information carriers are terabit-level media and their equivalents. The systemic integration of these information carriers with artificial intelligence and artificial neural network elements fundamentally transforms the technical characteristics and capabilities of such supersystems, as well as the hierarchical structures of their constituent subsystems.

These technologies have been developed in parallel by groups of researchers from several countries, including Japan and South Korea.

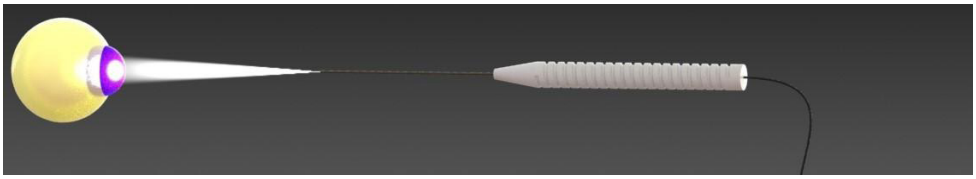
Figure 2. *Illustrates a disposable laser instrument with a radiation scheme directed into the patient's eyeball, in which several optimization conditions and techniques have been implemented to refine the emission parameters and spectral characteristics*



This has been achieved through the use of specialized drivers and optical mixers, enabling the combination of three laser diodes of equal power to produce an optimal radiation profile, spectrum, and output power.

As shown in the figure, the use of a disposable instrument necessitates extremely precise encoding in order to eliminate even the slightest possibility of errors during the configuration and optimization of radiation parameters. Such errors may arise when counterfeit disposable instruments are used, lacking the required calibration parameters and adaptability to the specific conditions of the surgical procedure.

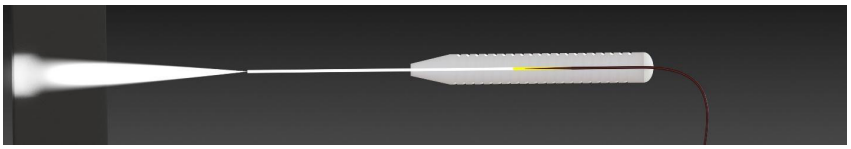
Figure 3. *Illustrates a configuration of a disposable laser instrument which, in conjunction with the optical components of the patient's eyeball, forms regions of optical aberration that facilitate a more adaptive integration of an active high-intensity laser beam within the optical conditions established in the treated eye*



These configurations of optical integration of radiation from the disposable instrument, as part of the innovative supersystem incorporating a comprehensive driver and other components of the ophthalmological laser instrument, are enabled by the presence of a continuous functional interconnection between the driver processors assigned to each of the three laser diodes and the elements of artificial intelligence and artificial neural networks.

The demonstrated configurational flexibility of the overall supersystem allows, in future modifications, for the confident integration of quantum computing technologies and their processor equivalents into control and monitoring systems, potentially in combination or symbiosis with advanced conventional computing and processing architectures, including electronic circuit boards manufactured using RITM technologies (dimension-selective metal etching techniques).

Figure 4. *Also illustrates a variant of a disposable laser instrument which, in conjunction with the optical components of the patient's eyeball, forms regions of optical aberration that facilitate a more adaptive integration of an active high-intensity laser beam within the optical conditions established in the treated eye. In this case, however, part of the adaptive function within the overall process is achieved through the application of various types of luminophores in the processing and coating of the optical cable (fiber)*



These configurations of optical integration of radiation from the disposable instrument, as part of the innovative supersystem incorporating a comprehensive driver and other components of the ophthalmological laser instrument, are additionally determined by the influence of the properties and capabilities of the luminophore. This is combined with the presence of a continuous functional interconnection between the driver processors assigned to each of the three laser diodes and the elements of artificial intelligence and artificial neural networks, which in this case are further tasked with the high-speed, detailed coordination of all factors forming the final technical characteristics of the disposable instrument.

The demonstrated configurational flexibility of the overall supersystem allows, in future modifications, for the confident integration of quantum computing technologies and their processor equivalents into con-

trol and monitoring systems, with already demonstrated ultra-high processing speeds. This may be achieved in combination or symbiosis with the most advanced forms of modern computing and processing architectures, including electronic circuit boards manufactured using RITM technologies (dimension-selective metal etching techniques), which – by virtue of their structural design and, in particular, interlayer spacing of approximately 50 microns – can increase processing speed and system responsiveness by orders of magnitude.

Figure 5. *Illustrates an innovative supersystem of a comprehensive laser instrument for ophthalmological applications, operating in the mode of configuration and optimization of radiation parameters*

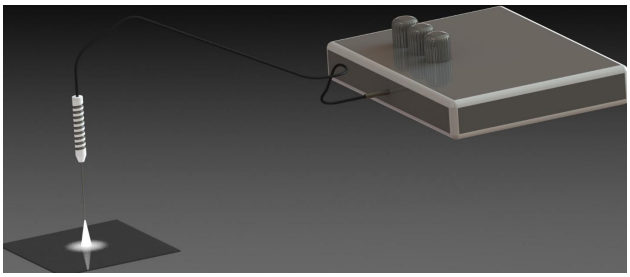
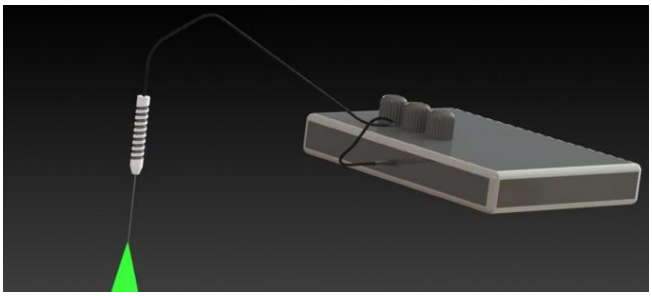


Figure 6. *Also illustrates an innovative supersystem of a comprehensive laser instrument for ophthalmological applications. In this system, three laser diodes operate simultaneously, each emitting radiation of a different wavelength. As in the previous examples, a disposable laser-emitting instrument is employed, which is connected to the specified laser radiation sources and their drivers via a precision optical cable, with the instrument located at one end and an encoding device at the other. The system as a whole incorporates luminophores, the function of which is to generate the required emission spectrum while simultaneously mitigating the impact of high-intensity, high-concentration laser radiation on the patient's physiological parameters*



To demonstrate the degree of novelty of the elements of this technology, it is appropriate to further present information on the foundational inventions from which this group of fundamentally new technologies has evolved.

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ADVANCED DEVICE-BASED TECHNOLOGIES IN COSMETOLOGY: SAFETY AND CLINICAL PROTOCOLS

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Abstract

This article provides a comprehensive overview of modern hardware techniques used in aesthetic medicine, such as laser, radiofrequency, ultrasound, and IPL light technologies. The focus is on the safety profile of these techniques, analyzing potential risks and methods for preventing and managing adverse events. Standardized clinical protocols are analyzed, which guide the choice of equipment and parameters based on the patient's skin type and individual features. The importance of following step-by-step algorithms for pre-procedure preparation and post-procedure rehabilitation is emphasized. The work highlights the critical importance of adhering to the principles of evidence-based medicine when incorporating innovative equipment into a cosmetologist's routine clinical practice, which is a prerequisite for achieving predictable, effective, and safe therapeutic outcomes.

Keywords: *hardware cosmetology, aesthetic medicine, clinical protocols, procedure safety, laser technologies, radiofrequency lifting, focused ultrasound, prevention of complications, skin rehabilitation, evidence-based medicine*

Relevance of the study

The study is becoming particularly relevant due to the dynamic development of aesthetic medicine and the steady increase in patient demand for non-invasive and minimally invasive methods for correcting age-related changes and dermatological problems.

High-energy equipment is regularly appearing on the market, including ablative and non-ablative lasers, microneedle RF lifting systems, and high-intensity focused ultrasound (HIFU) devices. These technologies significantly expand the therapeutic capabilities of doctors. However, the use of such powerful physical factors inevitably involves the risk of iatrogenic complications, such as deep burns, persistent post-inflammatory hyperpigmentation, scarring of tissues, and exacerbation of chronic dermatoses.

In the context of active product promotion and a sometimes careless attitude to the rules of using equipment, there is an urgent need for a thorough systematization of the accumulated global clinical experience. An extremely important step is to create a unified evidence base confirming the safety of the technologies used. It is also necessary to implement strict, regulated protocols that

will help minimize the likelihood of medical errors and ensure the predictability of aesthetic results.

The purpose of the study

The purpose of the study is to conduct a comprehensive analysis of the safety profile of modern hardware technologies used in cosmetology and the scientific systematization of standardized clinical protocols for their use.

The key objective of the work is to create clear algorithms for the personalized selection of physical exposure parameters based on skin phototype, aging morphotype and patient›s medical history. In addition, the aim of the study is to develop effective strategies for the prevention and management of potential adverse events at all stages of treatment and recovery.

Materials and research methods

The research is based on a comprehensive multidisciplinary approach, which includes an in-depth retrospective analysis of modern Russian and foreign scientific literature on dermatocosmetology.

We collected most of the data through a systematic search in the international medical databases PubMed, Cochrane Library, Scopus, and eLibrary. We filtered the publications for the last ten years. In our work, we used methods of meta-analysis of the results of randomized clinical trials, cohort studies, and detailed reports on clinical cases associated with complications after hardware interventions.

A comparative analysis of the official clinical recommendations of the international aesthetic communities and factory manuals of leading manufacturers of medical equipment was also carried out. Methods of statistical processing of epidemiological data on the frequency and nature of side effects were used to identify objective patterns. This made it possible to develop reliable algorithms for the safe use of high-intensity hardware techniques in everyday clinical practice.

The results of the study

The evolution of cosmetic surgery began at the end of the 19th century and is closely related to the introduction of electricity into clinical medicine. The first significant breakthrough was made in 1891, when the French physiologist Jacques Arsène d'Arsonval discovered the therapeutic effect of high-frequency pulse currents. This discovery led to the development of the darsonvalization method, which continues to be used today to stimulate microcirculation and treat inflammatory skin diseases. During the same time, in 1875, the American ophthalmologist Charles Michel used direct galvanic current to destroy hair follicles in the treatment of trichiasis. This became the basis for electroepilation, a method that has since been widely used in cosmetic surgery.

During the first half of the 20th century, aesthetic medicine primarily borrowed techniques from classical physiotherapy. Techniques such as iontophoresis, galvanization, and vacuum massage were introduced into practice. These methods allowed for non-invasive stimulation of cellular metabolism and improved the transdermal absorption of topical medications.

A true technological revolution in aesthetic medicine took place in the second half of the 20th century thanks to the invention and application of laser radiation. Following the creation of the first ruby laser by Theodore Maiman in 1960, extensive research into the effects of focused light on biological tissue began.

A major event that altered the course of industry development was the publication of the theory of selective photothermolysis by Rox Anderson and John Parrish in 1983. This concept scientifically proved the possibility of targeting the destruction of specific cells containing melanin, hemoglobin, or water using light energy at a precisely defined wavelength, without causing thermal damage to surrounding intact structures. This discovery provided a powerful impetus for the development of specialized systems for laser hair removal, treatment of vascular pathologies, and pigmentation disorders.

In the 1990 s, the first carbon dioxide and erbium laser devices for deep skin resurfacing were introduced on the market. These devices provided unprecedented results in reducing the appearance of wrinkles and scars, but they required long and difficult recovery periods for patients (Table 1).

Talitsa 1. *Ablative carbon dioxide lasers in cosmetology*

Indications	Advantages	Disadvantages and risks
1. Eliminate wrinkles and fine lines. 2. Treatment of scars (including post-acne). 3. Elimination of pigmentation. 4. Pore tightening. 5. Elimination of skin formations (warts, papillomas, etc.).	1. High efficiency in combating the signs of aging. 2. Long lasting results after several treatments. 3. The ability to adjust the depth of exposure.	1. The procedure can be painful and requires the use of anesthesia. 2. Recovery after the procedure takes a long period, which can vary from several days to several weeks. 3. There is a risk of hyperpigmentation and infection.

Since the beginning of the 21st century, the development of medical technologies has taken the path of minimizing tissue injury and speeding up the recovery process. In 2004, a revolutionary fractional photothermolysis technology was developed, which allows microscopic areas to be affected on the epidermis and dermis, preserving healthy cells around them for accelerated regeneration.

At the same time, non-laser correction methods were actively developing. IPL broadband pulsed light systems for non-ablative photorejuvenation, as well as RF radiofrequency lifting devices that stimulate neocollagenesis through deep controlled heating of the dermis, have become particularly popular. The last decade has been marked by the widespread introduction of HIFU technologies for non-surgical SMAS lifting, cryolipolysis devices for modeling body contours, and microneedle radiofrequency exposure systems (Chebanova I., 2025).

It should be noted that modern hardware cosmetology is a highly advanced branch of aesthetic medicine, where maintaining a balance between clinical effectiveness and patient safety is of utmost importance.

The global hardware cosmetology market is growing at a rate of 13–15% per year (CAGR), and is projected to exceed $18 billion by 2030. Over 70% of patients seeking aesthetic treatments prefer non-invasive hardware methods to plastic surgery. Approximately 45% of treatments today are performed using combined protocols (devices + injections) in order to maximize results (Chuhraev N., 2016).

The basis for successful work with laser, radiofrequency, and ultrasound systems is careful standardization of procedures and strict adherence to clinical protocols (Skiba R., 2025). These protocols, developed based on the principles of evidence-based medicine, define every step of the doctor's interaction with the patient. They begin with collecting anamnesis and determining the phototype of the skin on the Fitzpatrick scale and end with the selection of optimal physical parameters of exposure and the appointment of proper rehabilitation care.

The safety of procedures at the level of the devices themselves is ensured with modern monitoring and feedback systems. Modern platforms have built-in sensors that constantly monitor skin temperature, tissue electrical resistance, and the quality of the manipulator's contact with the skin. This avoids thermal burns caused by light and laser exposure. Multi-stage systems, such as contact sapphire glasses, dynamic cryogenic spraying, or powerful cold air blowing, are used to cool the skin.

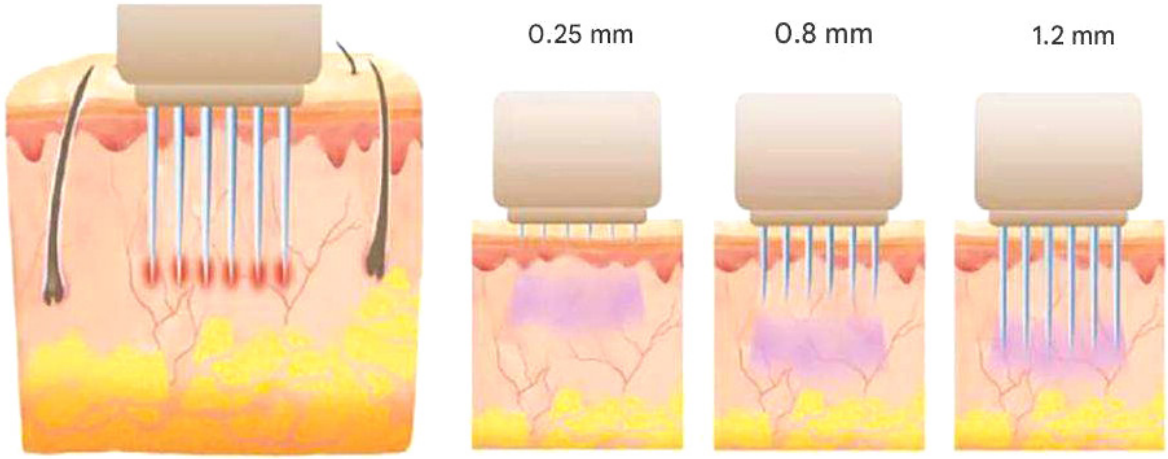
To protect the vision of the doctor and the patient, special glasses are used that block radiation of a certain wavelength. In recent years, manufacturers have been actively implementing artificial intelligence algorithms. These algorithms automatically analyze the level of melanin and skin hydration, which allows the doctor to choose safe energy parameters and minimize the risk of error.

Clinical protocols are clearly delineated depending on the physical energy used. When working with HIFU, the gold standard

of safety is the use of real-time imaging. This allows the doctor to accurately determine the depth of the musculo-aponeurotic layer (SMAS) and prevent accidental damage to large blood vessels or nerve nodes.

The protocols of microneedle radiofrequency lifting involve the use of strictly individual sterile nozzles with insulated needles. These nozzles conduct electric current only at certain depths, for example, 1.5 or 3.0 mm, reliably protecting the surface of the epidermis from overheating. In laser therapy and when working with broadband light (IPL), the key rule is to accurately observe the time of thermal relaxation of tissues. Before full-scale treatment of the area, it is necessary to conduct test flashes to assess the immediate erythematous skin reaction (Fig. 1).

Figure 1. *Operation diagram of needle RF lifting*



The safety of medical practice begins with careful patient selection. It is important to take into account absolute and relative contraindications, such as cancer, pregnancy, the presence of pacemakers, and acute dermatological conditions. Modern clinical guidelines increasingly use combined protocols that involve the consistent application of various physical factors within a single course.

One of the classic examples is the combination of none-ablative fractional photothermolysis and injectable biorevitalization. Another example is cryolipolysis combined with hardware lymphatic drainage. This approach allows doctors to use lower and gentler energy parameters for each device. This reduces the risk of post-traumatic hyperpigmentation and scarring. As a result, the aesthetic result becomes more pronounced, and the period of social rehabilitation of the patient is shortened.

Clinical results in numbers:

– SMAS lifting (ultrasound) – reduces the area of the skin flap by 15–25% in one procedure, and the visual lifting effect is enhanced within 3–4 months;

– Microneedle RF lifting – reduces the depth of skin wrinkles by 30–40% and reduces the severity of post-acne scars by 40–50% after a course of 3–4 procedures;

– Cryolipolysis is the hardware cooling of fat cells, which ensures the irreversible destruction of 20–25% of the local adipose tissue in the treatment area in one session;

– Laser hair removal (diode and alexandrite) – guarantees the removal of 85–95% of hair in the active growth phase in a course of 6–8 visits;

– Laser resurfacing (CO2) – renews up to 20–30% of the epidermis surface in one pass, significantly accelerating cellular metabolism.

Comparative analysis with injections and plastic surgery:

– The risk of complications when using hardware cosmetology is less than 1.5–2%. Most often, this is transient erythema or hyperpigmentation, which may occur if the procedure protocol is not followed. For comparison, in injectable cosmetology, the risk is 3–5% (for example, ischemia or granulomas), and in plastic surgery – 5–10%;

– The recovery time after hardware procedures ranges from 0 to 7 days, while surgical intervention requires from 14 to 60 days of full-fledged social rehabilitation;

– The life cycle of the client (LTV) using hardware techniques is 35–40% higher than with injection methods, since the latter require course application (for example, for laser hair removal, photorejuvenation, or body shaping).

Clinical studies confirm that the combination of hardware heating (e.g., RF) and injections (polylactic acid or collagen) can increase dermis density by 40–50% more effectively than using these methods separately. Over the past five years, there has been a significant increase in patients aged 25 to 30 who resort to preventive hardware procedures such as IPL therapy and Hydrafacial. The use of original certified devices approved by the FDA, CE, and Roszdravnadzor reduces the risk of adverse events by 90% compared to more affordable, non-certified analogues (Solianik M., 2025).

It is important to note that, despite impressive clinical results, the use of high-energy hardware technologies in cosmetology is fraught with significant difficulties. The main one is the insufficient level of specialist training. Deep academic knowledge in tissue physics, topographic anatomy, and dermatology is required to work with modern laser, radiofrequency, and ultrasound medical platforms. This necessitates continuous skill improvement and professional development for operators (Rudyeva A. D., 2022).

Unfortunately, in practice, specialists without specialized medical education or those who have completed only superficial commercial training often perform procedures. Failure to critically assess anamnesis, accurately determine tissue depth, and correctly select energy density can lead to serious complications such as deep thermal burns, subcutaneous fat atrophy, facial nerve damage during SMAS lifting, and the formation of persistent keloid scars.

Another significant problem in hardware cosmetology is the uncontrolled distribution of counterfeit and non-certified medical equipment. Many institutions, aiming to minimize capital costs, purchase shadow copies of premium devices that do not undergo rigorous technical and clinical trials.

Important safety systems, such as tissue impedance feedback and dynamic cooling of the epidermis, are missing or malfunctioning in such devices. Due to unstable pulse generation and unpredictable energy dissipation in tissues, the use of standardized treatment protocols becomes impossible. The situation is aggravated by the widespread practice of saving on consumables. Clinics use hacked programs to reuse disposable nozzles and insulated needles. This not only reduces clinical efficacy due to degradation of the conductors but also seriously violates infection safety protocols.

An important aspect that causes problems in the interaction between the doctor and the patient is the concealment of information and non-compliance with the rehabilitation regime. Patients often do not report the presence of absolute contraindications, such as fresh tanning, taking systemic retinoids, antidepressants, or photosensitizing antibiotics. The use of light or ablative technologies against the background of such conditions can lead to unexpected consequences, such as hyperpigmentation, persistent erythema, or serious violations of the skin regeneration process.

The situation is significantly complicated by aggressive marketing and promises of immediate results broadcast on social media. This leads to the formation of unrealistic expectations among patients, which puts psychological pressure on doctors. Doctors are then pushed to overestimate energy parameters to achieve instant results, blurring the line between therapeutic damage and irreversible tissue destruction.

We believe that solving the issue of insufficient qualifications requires government regulation and reform of postgraduate medical education. It is essential to introduce mandatory certification for each specialist, with regular confirmation of his or her practical skills on high-energy equipment.

The training should go beyond superficial commercial training provided by distributors and include in-depth academic study of the physics of hardware impact techniques, as well as mandatory cadaver practice to ensure a thorough understanding of topographic anatomy. Legislative consolidation of the right to perform aggressive hardware procedures solely for doctors who have undergone specialized retraining in cosmetology would minimize the risk of serious iatrogenic complications.

To eliminate the counterfeit medical device market, it is necessary to implement a mandatory, statewide digital labeling system that tracks medical devices from their production to the end user. This system should include end-to-end traceability, ensuring that all devices are authentic and safe for use.

Original medical device manufacturers should also take steps to protect their products by implementing hardware-level encryption and RFID tags based on chips. These technologies can prevent unauthorized use of devices, such as using gray market or hacked devices, and ensure that devices are not used multiple times after they have been disposed of. Regular technical audits by supervisory authorities, with the ability to confiscate non-compliant devices, will help ensure that clinics comply with infection safety standards and the predictability of treatment outcomes.

Overcoming communication barriers with patients and minimizing the negative effects of aggressive marketing can be achieved through strict standardization of legal support for medical procedures. The introduction of detailed digital medical history checklists integrated with unified electronic medical records to automatically verify prescriptions for antidepressants, retinoids, or photosensitizers, will eliminate the risk of withholding important information.

Expectation management should be based on ethical codes and a legal ban on the publication of unscrupulous advertising that promises instant results without proper rehabilitation. The use of objective hardware skin analysis systems before and after procedures can help relieve psychological pressure on doctors, prevent dangerous overestimations of energy parameters in order to achieve instant lifting, and focus on safe physiological tissue regeneration protocols.

Conclusions

Modern hardware cosmetology is a highly intelligent field of aesthetic medicine, where the effectiveness of treatment directly depends on strict compliance with safety rules and the use of scientifically proven clinical protocols.

The rapid development of laser, radiofrequency, ultrasound, and photosystems opens up new horizons for noninvasive rejuvenation, tissue repair, and treatment of dermatological diseases. However, as the equipment becomes more powerful and the physical parameters of the impact become more complex, a deep understanding of the basics is required.

Fundamental knowledge about the biophysics of optical and acoustic waves, topographic anatomy, and cellular response mechanisms is a cornerstone for preventing serious complications such as thermal damage, scarring, and persistent dyspigmentation.

The guarantee of patient safety today relies on a three-pronged approach, including the use of legally certified equipment, continuous professional development for doctors, and strict adherence to personalized protocols that consider the patient's morphotype, skin type, and medical history. The industry's transition from aggressive marketing to evidence-based principles, the introduction of prediagnostic hardware methods, and transparent communication form a strong foundation for successful treatment.

Long-term success will depend on a combination of innovative engineering solutions, rigorous government regulation, ethical standards, and deep medical expertise. This will allow us to achieve predictable and aesthetically pleasing results while maintaining patient health and safety.

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DEVELOPMENT OF STUDENTS' RESEARCH SKILLS IN STUDYING GENETICS THROUGH DIGITAL MODELING AND CASE STUDY METHODS

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Abstract

The article addresses the development of students' research skills during the study of the "Genetics" section in the school biology course. It highlights the transition from a knowledge-centric paradigm to a system-activity approach. The author describes a methodology integrating project-based learning, case technologies, and digital modeling (using the Virtual Genetics Lab as an example). The results of a pedagogical experiment conducted at Secondary School No. 350 in Tashkent are presented. It was established that the use of active learning methods and virtual simulators contributes to a 22% increase in academic performance and significantly enhances students' ability to independently formulate scientific hypotheses. The study confirms the effectiveness of the digital transformation of the educational process in forming scientific thinking and functional literacy among graduates.

Keywords: *education, biology teaching methodology, genetics, research skills, system-activity approach, project-based learning, case study, digital educational simulators, functional literacy*

Introduction

The modern transformation of the general education system is marked by a fundamental transition from a knowledge-centric paradigm to a system-activity approach (Vygotsky, L. S., 1999; Lerner, I. Ya., 1974). Within this model, the priority is no longer the mere transmission of ready-made knowledge, but the formation of students' universal action methods. In the context of the rapid progress of biomedical and convergent technologies, biological literacy ceases to be a highly specialized characteristic and transforms into an integral component of the functional literacy of a modern individual. This developmental vector is embedded in the requirements of the state educational standards for secondary education (Resolu-

tion of the Cabinet of Ministers of the Republic of Uzbekistan dated April 6, 2017). In this regard, one of the key tasks of secondary school is to prepare a graduate who is proficient in the methodology of scientific inquiry, possesses skills for analyzing multifactorial biological processes, and is capable of formulating evidence-based conclusions derived from empirical data.

Despite the high significance of the discipline, the "Genetics" section is traditionally classified as one of the most challenging to master in the school biology course. Students' cognitive difficulties are caused by a high degree of abstraction of genetic patterns and the complexity of interpreting microbiological processes. In pedagogical practice, there is often a dominance of reproductive teaching methods, which are reduced to the mechanical interiorization of Mendel's laws. Such an approach levels the research potential of the discipline. At the same time, it is genetics that possesses a unique didactic resource for developing research competencies through the study of phenotypic trait variability, genealogical analysis, and mutagenesis modeling.

Materials and Methods

The methodological framework of this research is grounded in the core tenets of the system-activity approach and the concept of problem-based learning (Makhmutov, M. I., 1977). The study was conducted at General Secondary School No. 350 in the Sergeli district of Tashkent.

The study sample comprised 40 ninth-grade students, who were divided into two groups of 20 participants each:

1. Experimental Group (9-"A"): Instruction was based on the integration of project-based methods, case technologies, and digital modeling. Particular emphasis was placed on working with virtual genetic simulators, specifically the *Virtual Genetics Lab*, which enabled students to model cross-breeding processes and perform real-time statistical data analysis (Virtual Genetics Lab (VGL II)).

2. Control Group (9-"B"): The educational process followed traditional methodology, focusing on the reproductive acquisition of theoretical material and the solution of standardized problems.

The set of research methods included a theoretical analysis of State Educational Standards (SES) and pedagogical literature, participant observation, the case study method (analysis of real-world genetic scenarios and pathologies), and methods of mathematical statistics to evaluate the significance of differences between the groups.

Results of the research and their discussion

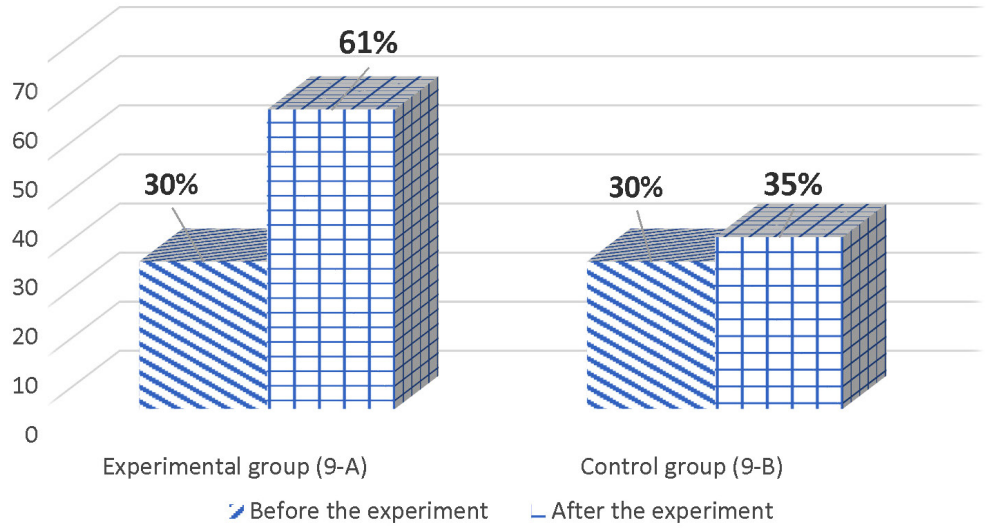
The testing of the developed methodological system within the educational process at Secondary School No. 350 in Tashkent confirmed the hypothesis regarding the high efficiency of integrating active learning methods. A comparative analysis of academic performance revealed a significant correlation between the forms of instructional organization and the quality of material acquisition. Based on the results of the assessment tests for the "Genetics" section, the average score in the experimental class (9-"A") was 22% higher than that in the control class (9-"B").

A qualitative analysis of the educational outcomes allowed for the identification of the following significant indicators:

- Improvement in operational skills: Students in the experimental group demonstrated a high degree of cognitive skill development when solving genetic problems of advanced complexity (including dihybrid crossing and sex-linked inheritance). While students in the control group frequently made algorithmic errors, the 9-"A" class exhibited the ability to make conscious strategic choices in their problem-solving approaches;
- Transformation of cognitive activity: The implementation of digital simulators (*Virtual Genetics Lab*) facilitated a transition from the mechanical internalization of Mendel's laws to a profound understanding of the dynamic mechanisms of heredity. Visualization and repeated virtual experimentation enabled students to "internalize" the statistical nature of genetics, as evidenced by their successful performance in tasks requiring the prediction of trait segregation in offspring;

- Development of research competencies: Students in group 9-»A» exhibited a high level of autonomy in formulating scientific hypotheses and interpreting mutagenesis modeling results. While participants initially experienced difficulties in establishing cause-and-effect relationships, by the final stage, 61% of them were able to provide reasoned explanations for discrepancies between modeling results and expected theoretical data;
- Project productivity: The effectiveness of the methodology is further evidenced by the fact that all 20 students in the experimental group successfully defended their individual mini-projects. An analysis of these projects revealed that the students learned not only to operate with biological terminology but also to apply it in analyzing real-world medico-genetic scenarios and pedigrees, indicating the successful formation of functional literacy.

Figure 1. *Dynamics of the ability to independently formulate a hypothesis*



The interpretation of the obtained quantitative data confirms the hypothesis that the integration of active learning methods into the study of genetics radically changes the quality of educational outcomes. A significant indicator of effectiveness was the 100% success rate in the implementation of individual research projects within the experimental group. In contrast to the control group, where student activity was limited to textbook-based learning, the students of group 9-”A” transitioned into the role of active subjects of scientific inquiry.

The key factor in intensifying the learning process was the use of digital modeling. The opportunity to conduct virtual “crosses” – the volume of which exceeded standard curriculum requirements by fourfold – helped overcome one of the primary challenges in school genetics: its abstract nature. Under a traditional approach, statistical patterns (Mendel’s laws) are often perceived by students as dogmas. However, working with large datasets in a digital environment allowed students to practically observe the stochastic (probabilistic) nature of heredity. This contributed to the formation of a scientific understanding that biological laws are realized not as rigid prescriptions, but as statistical trends.

The qualitative transformation of cognitive skills deserves particular attention. The increase in the ability to independently formulate hypotheses from 30% to 61% in the experimental group indicates a transition of thinking to a productive level. In the control group (9-”B”), where reproductive methods dominated, the stagnation of this indicator (an increase of only 5%) confirms that the traditional lecture-seminar system lacks sufficient resources to develop a researcher’s methodological apparatus.

The psycho-pedagogical effect of the methodology was reflected in a sharp rise in academic motivation. The subjective assessment of 85% of students in the experimental

group, who confirmed the practical significance of case technologies, indicates a solution to a fundamental problem in school education – the alienation of knowledge. Through solving problem-based situations (analyzing real genetic pathologies, predicting traits), abstract biological knowledge was transformed into personally meaningful experience. Thus, problem-based learning, coupled with digital tools, not only improves academic performance but also forms the foundation of scientific literacy required in the context of modern technological progress.

Conclusion

The study conducted at Secondary School No. 350 in Tashkent confirms that the "Genetics" section possesses exceptional potential for developing students' research competencies. Based on the data obtained, the following conclusions can be drawn:

1. The formation of research skills occurs most effectively through problem-solving and project-based work, where the student assumes the role of an active subject of inquiry.

2. The integration of digital simulators helps to overcome the limitations of school laboratory infrastructure and facilitates a transition to evidence-based learning through repeated modeling of biological processes.

3. The developed methodology fosters the growth of critical analysis and scientific thinking skills, which fully aligns with the requirements of modern educational standards and prepares graduates to function effectively in a high-tech society.

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Section 8. Philology and linguistics

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THE ETYMOLOGICAL AND PRAGMATIC ASPECTS OF PERSONAL NAMES IN MARY SHELLEY'S FRANKENSTEIN

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Abstract

This article examines the etymological origins and pragmatic functions of personal names in Mary Shelley's *Frankenstein* (1818). While the novel has been extensively analyzed from philosophical, psychological, and cultural perspectives, its anthroponymic system remains relatively underexplored. A total of eight main character names were analyzed: Victor Frankenstein, the Creature (unnamed), Elizabeth Lavenza, Henry Clerval, Alphonse Frankenstein, William Frankenstein, Justine Moritz, and Robert Walton. Combining etymological analysis and pragmatic-literary analysis, this research identifies patterns linking etymology and narrative function. The conducted analysis allowed the characters' names to be classified according to their thematic and ethical functions. Results indicate that Mary Wollstonecraft Shelley employs names as semiotic tools to reinforce themes of creation, ambition, morality, and alienation. The absence of a personal name for the Creature emerges as a deliberate pragmatic strategy emphasizing dehumanization and existential otherness. These findings contribute to broader literary onomastics and support the thesis that naming in Romantic literature operates as an ideological and emotional code rather than a neutral narrative device.

Keywords: *literary onomastics, pragmatics, etymology, Mary Shelley, Frankenstein, personal names, Romantic literature*

Introduction

Personal names in literature function not only as identifiers but also as semantic, psychological, and cultural markers. This research focuses on the personal names in Mary Shelley's Frankenstein, analyzing their etymological origins and narrative roles. The combined analysis shows how the choice and

use of names contribute to the ethical and philosophical dimensions of the novel. In Romantic literature, naming practices often articulate philosophical tensions of individuality, morality, and social belonging (Barczewska, 2020). Mary Shelley's Frankenstein offers a compelling field for such analysis, presenting characters whose names reveal deeper symbolic dimensions. As Yunusova (2021, p. 3007) points out, proper names in fiction play a significant role in organizing the structure of a literary text. Their systematic use conveys human relationships, nuances of intimacy, social roles, age, and other characteristics. In any narrative, a character is established in the reader's mind not only through their name, but also through appearance, personality traits, actions, thoughts, and distinctive speech.

Frankenstein is one of the first novels in the Gothic tradition and a landmark of Romantic literature. This novel, written in the early 19th century during the Romantic era, explores themes that were relevant at that time, such as horror, sin, the sublime, the conflict between human reason and the laws of nature, scientific ambition, and moral responsibility. Previous scholars have discussed the novel in terms of Gothic aesthetics (Botting, 2018), ethics of scientific ambition (Mellor, 1988), and existential identity (Knoepflmacher, 2009), yet its anthroponymic system has not been sufficiently examined from a linguistic perspective.

Thus, the present research aims to fill this gap by exploring the etymological roots and narrative functions of character names in Frankenstein. The analysis focuses on how names reflect character traits and emotional dynamics, and how the absence of naming, particularly in the case of the Creature, becomes a pragmatic aspect of literary and moral exclusion.

To achieve this goal, the following tasks are to be completed:

- To examine the origins and meanings of the characters' names in *Frankenstein;*
- To analyze how these names express the characters' personalities
- To explore the Creature's lack of a name as a way of showing his alienation;
- To show how names in the novel reflect moral and thematic functions.

Methods

This study employed a qualitative literary-linguistic methodology grounded in principles of etymological and pragmatic-literary analysis. The research design was interpretive and text-centered, focusing on how anthroponyms operate as semantic and narrative units within Mary Shelley's *Frankenstein* (1818).

The methodological framework consisted of three main components:

1. Etymological analysis. The etymology of each selected name was traced through Indo-European linguistic sources, with emphasis on Greek, Latin, Germanic, and Romance roots. Standard etymological dictionaries and online linguistic corpora were consulted to establish historically verifiable meanings, semantic shifts, and cultural connotations associated with each name at the time of the novel's composition and publication.

2. Pragmatic-literary analysis. Each name was examined within the narrative context to determine its pragmatic function, including its role in character construction, thematic development, emotional framing, and narrative point-of-view structuring. Principles of literary pragmatics and speech-act theory were applied to assess the communicative power of naming and the effects produced by the absence of a name in the case of the Creature.

Corpus and Dara Sources. Primary data consisted of personal names appearing in the 1818 edition of *Frankenstein* by Mary Shelley. Secondary sources included scholarly literature on Romanticism, literary onomastics, narrative pragmatics, and Shelley studies from peer-reviewed journals and academic monographs.

Sample of Names Analyzed. Victor Frankenstein, the unnamed Creature, Elizabeth Lavenza, Henry Clerval, Alphonse Frankenstein, William Frankenstein, Justine Moritz, and Robert Walton.

Analytical Procedure

The analysis proceeded in three stages:

1) lexical-etymological identification and meaning extraction,

2) contextual interpretation of name usage within specific narrative passages and

3) synthesis of etymological and pragmatic insights to determine symbolic and thematic functions.

This multi-layered approach ensured both linguistic precision and literary contextualization, aligning the study with established research practices in comparative literature and linguistic anthropology.

Results

The name of the main character, Victor, in the novel comes from Latin roots and means "a conqueror" (Arthur, 1857, p. 289). Therefore, this name signifies strengths and the achievement of goals. In the novel, Victor strives to defeat death by creating life artificially, thereby attempting to take the place of God. His obsession with this goal is shown in his speech:

No one can conceive the variety of feelings which bore me onwards, like a hurricane, in the first enthusiasm of success. Life and death appeared to me ideal bounds, which I should first break through, and pour a torrent of light into our dark world (Shelley, 2016, p. 26).

Thus, this passage expresses Victor's strong desire to cross the boundaries between life and death. However, he creates a monster by mistake and abandons it without even naming it. As a result, his creation suffers, pursues revenge, and ultimately destroys Victor's entire family. After numerous tragedies, Victor searches for his creation for a long time to kill it.

The surname of Victor Frankenstein was not found in traditional etymological dictionaries. According to Palaeas (2005), it literally means "marked in stone" and is probably related to the ruins of the castle mentioned by Mary Shelley in her 1814 travel diary. The surname may function as a metonymic device: all but one of the Frankenstein family members lie dead, and their surname, "marked in stone," becomes a grim reminder of Victor's inability to take moral responsibility for his creation (p. 211). Frleta and Frleta (2020, pp. 53–54) note that Mary Shelley may have chosen the surname Frankenstein because she once lived near a village of the same name. The name can also be interpreted as a combination of frank "free" and stein "stone", reflecting both Victor's scientific freedom and his resolute, steadfast character.

In the novel, Victor's best friend since childhood is Henry Clerval. His name is derived from the Saxon *Honoricus* and means "honorable" (Arthur, 1857, p. 281). As a character, Henry perfectly reflects the meaning of his name through his kind and noble nature. He is described in the novel as follows: *"Clerval was no natural philosopher. His imagination was too vivid for the minutia of science. Languages were his principal study..."* (Shelley, 2016, P. 34–35). Thus, in the novel, he is the complete opposite of Victor in interests and character. While Victor is obsessively focused on science and experiments, he is interested in literature and languages. He also values friendship and kindness, supporting Victor in his most difficult times.

One of the most significant female characters who plays an important role in Victor Frankenstein's life is Elizabeth Lavenza. Her name originates from Hebrew, meaning "Oath of God" (Arthur, 1857, p. 293). In the novel, she is the adopted daughter of the Frankenstein family. She lives a harmonious life, providing Victor with the necessary emotional support. The following lines describe this character: *"This period was spent sadly; my mother's death, and my speedy departure, depressed our spirits; but Elizabeth endeavoured to renew the spirit of cheerfulness in our little society..."* (Shelley, 2016, p. 20). Following the fragment, Elizabeth tries to maintain an optimistic atmosphere in the family despite the grief, thus bringing joy back into their lives. She cares for others, which reveals her kind and caring nature. Her efforts also show that even in difficult times, a person can be a source of comfort to those around them.

Another important character is Alphonse, the head of the Frankenstein family. The name Alphonse, spelled as Alphonso in etymological sources, comes from Gothic *Helpuns* and means "our help" (Arthur, 1857, p. 274). Shelley appears to choose this name specifically to show the character's kind and caring nature, who is ready to protect his family. In contrast to Victor, who prioritizes science, Alphonse places family above all else. As stated in the following lines:

When my father became a husband and a parent, he found his time so occupied by the duties of his new situation, that he re-

linquished many of his public employments, and devoted himself to the education of his children… (Shelley, 2016, p. 15).

This fragment confirms the idea that Alphonse is sacrificing his own time and personal interests while engaged in the upbringing and education of his children. When Victor's actions lead to the death of his closest people, Alphonse experiences profound grief, leading to his death. The comparison between father and son suggests that true strength lies not in the pursuit of excessive personal ambitions, but in responsibility and care for others.

Victor has a younger brother named William. The name is derived from the German *Wilhelm*, meaning "the shield or defense of many" (Arthur, 1857, p. 290). His tragic fate shows how fragile and vulnerable children are to the mistakes of others, as can be seen in the following extract: *"William, the youngest of our family, was yet an infant, and the most beautiful little fellow in the world…"* (Shelley, 2016, p. 19). In these lines, he is depicted as a symbol of childlike purity and innocence. He becomes the first victim of the Creature, and after his death, a chain of misfortunes begins, including the execution of Justine Moritz, the Frankenstein family's maid, after which Victor starts to experience profound guilt. Although the name William means "defender," he cannot protect himself from the Creature because of his brother's actions, which makes his name an ironic element in the novel.

The next victim of Victor's Creature is Justine Moritz. In etymological sources, the name appears in its original Latin form, *Justin*, denoting "just" and "virtuous" (Arthur, 1857, p. 283). In the novel, she is perceived not only as a servant but as a family member, having grown up with Victor and Elizabeth, helping care for the household. Despite her honest nature, Justine is blamed for William's death, as described in the following excerpt: *"Several strange facts combined against her, which might have staggered anyone who had not such proof of her innocence as I had"* (Shelley, 2016, p. 42). Following the extract, it becomes clear that she is wrongly accused when a miniature of William's mother is found in her pocket. Although the evidence appears overwhelming, Victor and Elizabeth remain convinced of her innocence. In court, Justine, who is innocent, confesses to murder under moral pressure from the priest, as shown in the following excerpt: *" I did confess; but I confessed a lie. I confessed, that I might obtain absolution"* (Shelley, 2016, p. 45). After her confession, Justine is found guilty and executed, despite Elizabeth's protests. Later, Victor learns that the Creature framed Justine. In the novel, her image is a symbol of an innocent victim suffering for someone's guilt. Moreover, her fate creates an ironic contradiction between the meaning of her name and the real injustice she experienced.

The most profound onomastic gesture in the novel is the absence of a personal name for the Creature. Within the framework of pragmatic linguistics, naming constitutes an act of recognition, conferring social existence, legal subjectivity, and symbolic belonging (Austin, 1975). Shelley's refusal to name the Creature is not a passive omission but an intentional act of narrative erasure. The repeated use of labels such as daemon, fiend, and wretch functions as linguistic exclusion and moral stigmatization, producing what contemporary theory terms symbolic violence. This systemic denial of linguistic identity mirrors broader Romantic concerns with the limits of human empathy, the construction of the Other, and the ethical implications of creation without care. As Radonjic Strid (2020, p. 10) notes, names are traditionally given to children by their parents; however, Victor, as the only parental figure for the Creature, fails to fulfill this role. He refers to his creation solely with derogatory terms such as "wretch" and "monster," which significantly influence the development of the Creature's identity.

The narrator of the story is Robert Walton. As an English sailor and a commander of an expedition to the North Pole, he strives to achieve a great discovery and to become renowned in the field of geography. His name, Robert, is derived from the Saxon words *rod* "counsel" and *beorht* "bright", giving the overall meaning "famous in counsel" (Arthur, 1857, p. 287). The novel begins with letters from Walton to his sister, Margaret Saville, in which he describes the meeting with Victor and retells his narrative. There are notable

similarities between him and Victor, particularly in his strong desire for discovery, as reflected in his words:

... I feel my heart glow with an enthusiasm which elevates me to heaven; for nothing contributes so much to tranquilize the mind as a steady purpose, a point on which the soul may fix its intellectual eye. This expedition has been the favourite dream of my early years... (Shelley, 2016, p. 6).

These words reveal Walton's strong ambition for research, reflecting his childhood dream of accomplishing something remarkable. He is confident in his aspiration, but his passion manifests as inspiration rather than obsession. His speech also conveys the joy of a man who fully dedicates himself to a particular goal. However, unlike Victor, Walton knows when to temper his ardor. Drawing on Victor's tragic story, he reflects on the dangers of unchecked ambition and exemplifies this in the following fragment:

I have lost my hopes of utility and glory; I have lost my friend. But I will endeavour to detail these bitter circumstances to you, my dear sister; and, while I am wafted toward England, and towards you, I will not despond (Shelley, 2016, p. 119).

His writing demonstrates Robert's critical thinking and his ability to make wise decisions by learning from the mistakes of others. After hearing Victor's story and losing his friend, he realizes that excessive ambition can lead to tragedy. Consequently, he decides to stop the expedition and turn the ship back, protecting his crew from danger. Through this character, it can be concluded that the pursuit of achievement can be positive if combined with responsibility, whereas ignoring his trait may result in serious consequences.

The analysis shows that the names of the characters in *Frankenstein* are not accidental. They carry important semantic and symbolic meanings that contribute to the interpretation of the novel. Mary Shelley uses names as a literary device through which she reveals the inner world of her characters and draws attention to the key ideas of the narrative. The etymology and pragmatic function of the names illuminate the motives behind the characters' actions and clarify how their personal qualities shape the events of the story. In several cases, Shelley also introduces an element of irony, allowing a striking contrast between the meaning of a name and the fate of its owner.

Conclusion

This investigation confirms that anthroponyms in Mary Shelley's Frankenstein function as highly charged semiotic units, weaving together etymological inheritance, narrative pragmatics, and Romantic ideology. Far from serving as inert labels, personal names operate as discursive engines: they choreograph moral alignments, foreshadow character arcs, and dramatise the novel's central dialectic between promethean aspiration and ethical accountability. By embedding Greco-Latin, Germanic, and Biblical resonances within her character roster, Shelley constructs a multilayered linguistic matrix through which creation, alienation, and responsibility are simultaneously asserted and problematised.

The Creature's namelessness remains the novel's most radical onomastic gesture. This purposeful linguistic void foregrounds contemporary debates on personhood, social recognition, and the ethical duty of the creator toward the created. In denying her "modern Prometheus" the ontological anchor of a proper name, Shelley crystallises Romantic anxieties about the instability of identity and the perils of technological hubris untempered by compassion. The resulting discursive exclusion transforms nomenclature into a site of symbolic violence – one that shapes the reader's moral imagination as powerfully as the narrative events themselves.

Collectively, these insights extend existing scholarship by demonstrating how onomastics supplies the critical infrastructure of Shelley's thematic architecture. Names in Frankenstein are not mere ornaments; they are ideological signposts guiding readers through an exploration of the limits of human dominion, the fragility of ethical responsibility, and the contested boundaries of the human. In this respect, the novel anticipates later theoretical frameworks – from structuralist semiotics to post-Foucauldian discourse theory, which position language as a primary locus of power and subject formation.

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Section 9. Transportation

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SUPPLY CHAIN INTERDEPENDENCIES AND THE MACROECONOMIC ROLE OF SURFACE FREIGHT TRANSPORTATION: EVIDENCE FROM A JOINT PROBABILISTIC FORECASTING AND STOCHASTIC ROUTING ARCHITECTURE

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Golden Route Express

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Abstract

Surface freight transportation is both a cost input and a demand signal within supply chains, yet the feedback mechanisms through which carrier-level operational decisions affect macroeconomic outcomes remain theoretically underspecified and empirically difficult to trace. This paper investigates those mechanisms by analyzing a hardware-implemented freight route optimization system that unifies probabilistic cargo load forecasting and vehicle routing within a single stochastic objective function. Validated against three baseline configurations on a 14-day operational dataset covering 118 Class 8 vehicles, the architecture reduced total daily route mileage by 29.7%, deadhead mileage by 34.1%, and improved on-time delivery rates from 81.3% to 93.6%. The gap between a traffic-aware commercial routing system (14.2% mileage reduction) and the proposed architecture (29.7%) demonstrates that demand uncertainty quantification contributes more to carrier-level cost reduction than does road-network intelligence alone.

Keywords: *surface freight transportation, supply chain interdependencies, stochastic vehicle routing, probabilistic load forecasting, macroeconomic indicators, deadhead mileage reduction, reinforcement learning, Proximal Policy Optimization*

Introduction

Surface freight trucking carries approximately 70% of all freight tonnage moved domestically in the United States, making it structurally non-substitutable within supply chains at the temporal resolutions relevant to manufacturing and retail operations (Coyle et al., 2016). Because transportation

costs enter the cost function of virtually every downstream sector, inefficiencies in dispatch architecture do not remain confined to the carrier sector but propagate outward through input-output linkages. Hummels (2007) documented that a one-percentage-point reduction in ad-valorem transportation costs is associated with trade volume responses comparable to tariff reductions of equivalent magnitude, an estimate that implies substantial aggregate welfare consequences from sustained carrier-level inefficiencies.

Existing freight optimization literature has addressed operational performance primarily within the deterministic Vehicle Routing Problem (VRP) framework initiated by Dantzig and Ramser (1959) and extended by Solomon (1987) to accommodate time windows. These formulations assume demand volumes and locations are known at route construction, an assumption that holds tolerably well for parcel delivery in urban distribution but breaks down in long-haul truckload operations where a substantial fraction of freight is tendered on the spot market within hours of pickup (Crainic and Laporte, 1997). Stochastic extensions of the VRP, reviewed by Gendreau et al. (1996), introduced parametric demand uncertainty but relied on fixed distributional assumptions that do not adapt to the heterogeneous and non-stationary demand processes observed in live freight networks. The integration of machine learning forecasting into routing pipelines has been proposed repeatedly in recent literature (Nazari et al., 2018), but nearly all such proposals are validated on synthetic benchmark instances rather than operational carrier data with real regulatory constraints.

Materials and Methods

The system under analysis comprises five interconnected computational subsystems: a Data Ingestion and Normalization Layer, a Predictive Load Forecasting Engine, a Route Optimization Module, a Reinforcement Learning Feedback System, and a Dispatcher Interface.

Input data streams include ELD telemetry (GPS, speed, fuel state, hours-of-service), shipper order records (origin/destination codes, commodity, weights, appointment windows), and road network updates from HERE Technologies at five-minute intervals.

The fifth input category is the macroeconomic and freight market feed, sourced from the Cass Freight Index, the DAT Truckload Volume Index, and the EIA weekly retail diesel fuel price series. The ISM Manufacturing PMI and the U. S. Census Bureau Advance Monthly Retail Trade Survey are incorporated as weekly-updated conditioning variables for forecasting horizons exceeding 48 hours. This design choice is theoretically motivated: PMI is an established leading indicator of industrial production with a documented lead of three to six weeks over confirmed freight tender volumes (Coyle et al., 2016), making it informative for 48-to-72-hour demand prediction in a way that carrier-internal order data cannot be.

The forecasting engine implements a multi-branch deep neural network producing probabilistic forecasts per freight lane at horizons of 6, 12, 24, 48, and 72 hours. Three parallel branches capture distinct aspects of demand: a bidirectional GRU with self-attention over seven-day hourly sequences (long-range temporal patterns); a Temporal Convolutional Network over the 32 most recent hours (short-range trends); and a Graph Attention Network over a freight lane interaction graph (spatial demand spillovers between connected corridors). The three branches' outputs are concatenated into a 1,792-dimensional joint representation, processed by two fully connected layers, and projected by a probabilistic head generating parameters of a mixture of four Gaussians for each forecast horizon. The training objective combines negative log-likelihood of observed volumes under the predicted mixture with a calibration regularization term weighted at 0.10, penalizing squared deviation between empirical coverage and nominal probability at the 50th, 80th, and 95th percentiles.

The Route Optimization Module formulates a Stochastic Capacitated Vehicle Routing Problem with Time Windows (SCVRPTW) using sample-average approximation with N = 50 demand scenarios drawn from the forecasting engine's output distributions. Each vehicle is characterized by payload capacity, volumetric capacity, current GPS position, hours-of-service availability under the FMCSA 11-hour driving limit, 14-hour duty limit, and current fuel level. The optimization objective for scenario s is:

$$C_s = w_1 \times D_s + w_2 \times H_s + w_3 \times P_s + w_4 \times G_s$$

where D_s is total vehicle distance in miles, H_s is deadhead distance, P_s is total time-window violation penalty at $150 per violation-hour, G_s is total fuel consumption in gallons, and the default weights are w_1=0.30, w_2=0.35, w_3=0.25, w_4=0.10 The solver combines simulated annealing with adaptive cooling and ant colony optimization with pheromone evaporation rate ρ=0.10, exchanging best-so-far solutions between components every 200 iterations.

A Reinforcement Learning Feedback System models the dispatch process as a finite-horizon Markov decision process and applies PPO-Clip with clipping ratio 0.20 to update a transformer-pointer routing policy from realized outcomes. Operator overrides logged through the Dispatcher Interface are transmitted as supplementary training signals, enabling the policy to incorporate dispatcher expertise not captured in the quantitative reward function.

Four configurations were evaluated on a 14-day operational dataset from a Midwest regional carrier: 118 Class 8 vehicles, 847 average daily freight moves, 94 distinct freight lanes. A secondary generalization validation was conducted on a Southeast carrier with 76 vehicles over 12 days. Configuration A: deterministic CVRP, confirmed orders only, no forecasting. Configuration B: gradient-boosted point-estimate forecasting feeding the same deterministic CVRP. Configuration C: commercial traffic-aware routing, real-time road network, no demand forecasting. Configuration D: the full joint probabilistic forecasting and stochastic routing architecture described above. All configurations operated on identical input data streams and were evaluated against the same realized operational outcomes.

Results

Table 1 reports the comparative performance results across all four configurations on the Midwest carrier dataset.

Table 1. *Performance Evaluation Across Four System Configurations (Midwest Carrier Dataset, N = 118 Vehicles, 14 Operational Days)*

Performance Metric	Config. A: Deterministic CVRP	Config. B: Point-Forecast CVRP	Config. C: Traffic-Aware Routing	Config. D: Proposed System
Total Daily Route Mileage	23.847 mi (baseline)	21.134 mi (–11.4%)	20.457 mi (–14.2%)	16.774 mi (–29.7%)
Daily Deadhead Mileage	5.213 mi (baseline)	4.748 mi (–8.9%)	4.832 mi (–7.3%)	3.435 mi (–34.1%)
On-Time Delivery Rate	81.3%	86.7%	88.4%	93.6%
Avg. Fuel per Shipment (gal)	14.8	13.1	12.9	10.3
Fleet Asset Utilization	67.4%	72.1%	69.8%	84.5%
24-hr Forecast MAPE	N/A	18.3%	N/A	9.1%

Two results deserve specific attention for the argument that follows in the Discussion. First, the 24-hour forecast MAPE of 9.1% achieved by Configuration D compares with 18.3% for the gradient-boosted point-estimate model in Configuration B. This improvement is attributable to the combination of the multi-branch architecture (which captures both temporal dynamics and lane-network spillover structure) and the mixture-of-Gaussians probabilistic output (which retains uncertainty rather than collapsing it to a scalar). Second, the gap between Configuration C (traffic-aware routing, 14.2% mileage reduction) and Configuration D (29.7%) is not attributable to superior road-network

modeling but to the presence of demand uncertainty quantification in the optimization objective. Configuration C has access to the same real-time road network data as Configuration D; its inferior mileage performance reflects what happens when a solver optimizes vehicle movement without knowing where freight is likely to materialize.

Discussion

What prior work has not resolved is the empirical magnitude of this advantage under real operational conditions with regulatory constraints. The 29.7% route mileage reduction achieved here exceeds improvements reported in simulation-based stochastic VRP studies, which typically report 10-to-20% gains over deterministic baselines (Crainic and Laporte, 1997). The difference is partly attributable to the quality of probabilistic demand forecasts feeding the solver: a stochastic VRP is only as good as the distributional inputs it receives, and a 9.1% MAPE over 24-hour horizons provides substantially more informative distributional inputs than the parametric assumptions used in classical SVRP implementations.

Unlike attention-based policy networks validated on synthetic instances (Nazari et al., 2018), the present architecture embeds FMCSA hours-of-service constraints as hard action-space boundaries, making assignments legally compliant by construction. The 7.2% cost reduction attributable to RL adaptation over 14 days also suggests that the policy improvement trajectory had not plateaued at the end of the validation window, which implies that reported results represent a lower bound on long-run performance.

The comparison with traffic-aware routing (Configuration C) is arguably the most practically relevant result in Table 1. Configuration C, with full real-time road network updates, achieves a deadhead reduction of only 7.3%, compared with 34.1% for Configuration D, which uses the same road network data but additionally solves for demand uncertainty. Traffic-aware routing improves a given assignment; it does not determine which corridors to pursue in the first place. The assignment decision, informed by probabilistic demand forecasts anchored to macroeconomic covariates, drives a larger share of operational cost variation than does movement efficiency given a fixed assignment.

At the firm level, the improvement in on-time delivery rate from 81.3% to 93.6% directly reduces the inventory safety stock requirements of receiving shippers. Chopra and Meindl (2016) estimate that for a manufacturer with annual sales of $500 million and a logistics cost share of 8%, a reduction in lead time standard deviation consistent with this service level improvement corresponds to a reduction in cycle inventory holding costs of 12 to 18%.

At the corridor level, the Adaptive Corridor Management module partitions the freight network into hexagonal H3 cells and generates capacity augmentation recommendations when forecasted corridor utilization exceeds 0.85, positioning vehicles anticipatorily before confirmed tenders materialize. At the macroeconomic level, the fuel reduction from 14.8 to 10.3 gallons per shipment (30.4%) deserves attention beyond its carrier-level cost implications. Freight transportation accounts for approximately 25% of U.S. transportation sector CO2 emissions (Bureau of Transportation Statistics, 2023), and fuel consumption is the dominant variable cost driver for truckload carriers. Efficiency gains of this magnitude, if adopted broadly across the Class 8 fleet, would reduce both the cost-per-ton-mile of freight transportation and the carbon intensity of goods delivery.

Conclusion

The evidence presented in this paper supports two conclusions that are relevant both to transportation operations research and to freight economics. The first is operational: a joint probabilistic forecasting and stochastic routing architecture achieves efficiency gains substantially exceeding those of traffic-aware routing and point-estimate forecasting, with the decisive differentiator being the quality of demand uncertainty quantification rather than road-network modeling. The second is macroeconomic: the transmission channels connecting carrier dispatch decisions to supply chain outcomes are identifiable and quantifiable. Deadhead mileage reductions aggregate into systemic freight cost decreases; delivery reliability improvements

reduce shipper safety stock requirements and working capital costs; anticipatory corridor positioning dampens spot-rate volatility and its pass-through into delivered goods prices.

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