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

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Abstract

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

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

Introduction

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

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

Among anthraquinone compounds, alizarin (1,2-dihydroxyanthraquinone) occupies a historically significant position as one of the earliest naturally derived organic dyes. Initially extracted from the roots of the madder plant (Rubia tinctorum), alizarin was extensively utilized in traditional textile dyeing processes for centuries (Bechtold T., Mussak R., 2009). The later development of synthetic alizarin production marked a transformative achievement in industrial organic chemistry and enabled the transition from natural dye extraction to large-scale chemical manufacturing (Graebe C., Liebermann C., 1869). This advancement greatly expanded the industrial importance of anthraquinone pigments in textiles, inks, polymer additives, artistic pigments, and protective surface coatings (Buxbaum G., Pfaff G., 2005). In contemporary research, alizarin derivatives are additionally investigated as functional compounds for electrochemical devices, sensing technologies, coordination chemistry, and photonic systems (Kalyanasundaram K., 1992).

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

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

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

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

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

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

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

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

Research method

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

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

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

Preparation of Alizarin Pigment

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

Condensation Process

The initial reaction stage was conducted in a 250 mL three-necked glass reactor equipped with a reflux condenser, mechanical agitator, thermometer, and electrically controlled heating system. This configuration ensured stable thermal conditions and efficient mixing throughout the synthesis.

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

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

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

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

Cyclization and Aromatic Stabilization

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

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

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

The simplified overall synthesis pathway may be represented as:

Phthalic anhydride + Catechol → Alizarin + H_2O

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

Neutralization and Product Purification

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

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

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

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

Determination of Pigment Yield

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

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

where:

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

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

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

Results analysis

Structural Formation Mechanism of Alizarin Pigment

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

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

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

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

X-Ray Diffraction Analysis

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

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

The reflections appearing in the 24–28° region are associated with π–π stacking interactions between planar anthraquinone structures. Such intermolecular interactions promote structural compactness, reduce pigment solubility in organic solvents, and improve physicochemical stability.

The coexistence of sharp diffraction peaks and broadened background regions suggests the simultaneous presence of crystalline and amorphous domains. This semi-crystalline organization is advantageous for industrial pigment systems because it combines sufficient structural order with improved dispersibility in coating matrices.

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

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

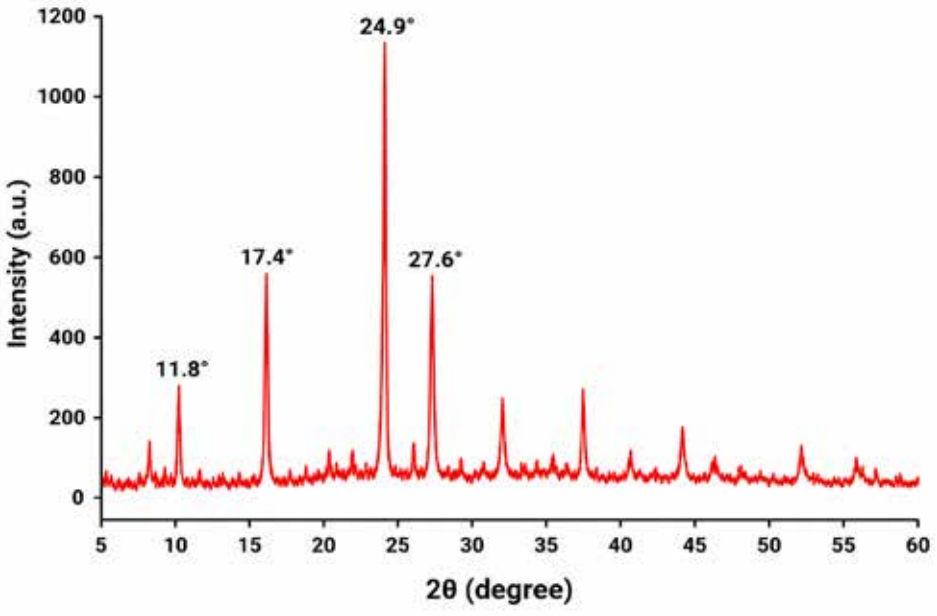
where:

D is the crystallite size;
K is the Scherrer constant;
λ is the X-ray wavelength;
β is the full width at half maximum;
θ is the diffraction angle.

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

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

Figure 1. *XRD pattern of the synthesized alizarin pigment*



The principal diffraction peaks obtained from the XRD analysis together with the corresponding interplanar spacing values, relative intensities, and crystallographic plane assignments are summarized in Table X. The diffraction reflections observed at 2θ values of 11.8°, 17.4°, 24.9°, and 27.6° confirm the formation of an ordered anthraquinone-derived semi-crystalline pigment structure.

Table 1. *XRD Structural Parameters of Synthesized Alizarin Pigment*

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

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

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

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

Thermal Behavior of the Synthesized Pigment

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

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

Stage I (50–140 °C)

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

Stage II (220–350 °C)

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

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

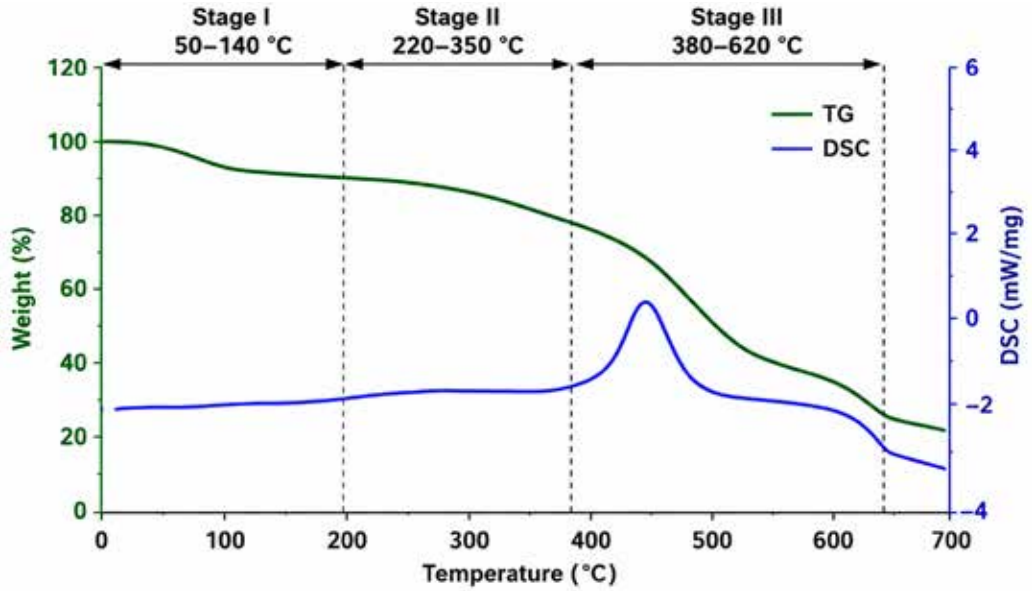
Stage III (380–620 °C)

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

Simultaneously, the DSC thermogram displayed pronounced exothermic peaks near 430–450 °C, which are associated with oxidation and carbonization reactions of aromatic molecular fragments. Despite progressive thermal degradation at elevated temperatures, approximately 20% residual mass remained at 700 °C, indicating the formation of thermally stable carbonaceous residue.

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

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



Pigment Performance Properties

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

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

The synthesized pigment also demonstrated thermal resistance up to approximately 250 °C, confirming its suitability for thermally cured coating technologies and polymer processing operations.

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

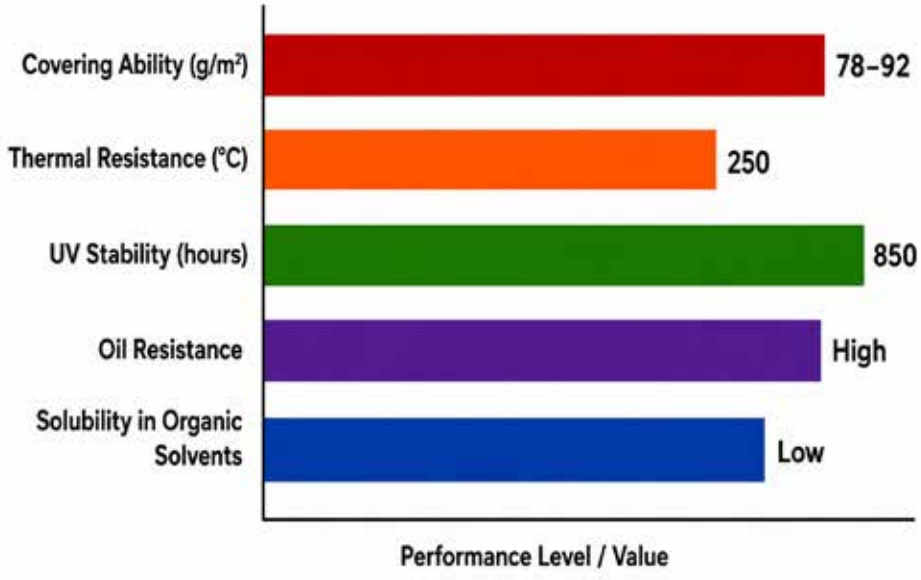
The pigment additionally demonstrated high oil resistance and low solubility in organic solvents. Reduced solubility is highly advantageous because it minimizes pigment migration and bleeding phenomena while improving long-term coating durability and color retention.

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

Table 2. *Performance properties of the synthesized alizarin pigment*

Property	Value
Covering ability	78–92 g/m²
Thermal resistance	250 °C
UV stability	850 h
Oil resistance	High
Solubility in organic solvents	Low

Figure 3. *Performance properties of the synthesized alizarin pigment*



Industrial and Technological Perspectives

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

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

The use of phthalic anhydride as the primary precursor provides several technological advantages, including relatively low raw-material cost, good industrial availability, synthetic scalability, and high process reproducibility. Moreover, the developed synthesis route does not require highly sophisticated processing equipment, which increases its industrial feasibility.

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

Conclusion (discussion)

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

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

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

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

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

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

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