Synthesis and application of a coumarin-derived dye for sustainable dyeing of polyester fabric

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Abstract

Purpose – This study aims to synthesize a coumarin-derived dye and evaluate its application in polyester fabric dyeing, focusing on its potential as a safer alternative to hazardous disperse dyes. By examining the dye's fastness, fluorescence, thermal behavior and theoretical binding interactions, this research supports more sustainable practices in textile processing.

Design/methodology/approach – The coumarin dye, 7-diethylamino-3-acetylcoumarin, was synthesized via the Knoevenagel reaction. Polyester fabrics were dyed using this coumarin dye under various conditions, including acidic and alkaline. Dyeing performance was evaluated based on washing, rubbing and light fastness tests, with particular attention to reductive washing for optimal results. The dye's structural characteristics were analyzed through Fourier transform infrared spectroscopy (FTIR), ultraviolet—visible (UV–Vis) and nuclear magnetic resonance (NMR) spectroscopy. Thermogravimetric analysis assessed thermal stability and degradation behavior. Density functional theory simulations were conducted to elucidate dye–fiber interaction mechanisms at the molecular level. In addition, in vitro cytotoxicity was tested using human skin fibroblast (CCD-1079Sk) cells.

Findings – The coumarin-derived dye exhibited excellent dye affinity and colorfastness on polyester fabrics, especially in acidic conditions with a 45-minute dyeing process followed by reductive washing. No cytotoxic effects were observed in human skin fibroblast cells, underscoring its potential as a safer alternative to conventional synthetic dyes. UV–Vis spectroscopy confirmed strong absorption properties, making the dye suitable for various textile applications.

Research limitations/implications – The study focused on polyester fabric; future research should extend the application to other textile types. Moreover, further investigation into aquatic degradation pathways and industrial-scale applicability is needed to fully validate environmental benefits.

Practical implications – The findings suggest that coumarin-derived dyes could provide a safer and more environmentally friendly alternative to disperse dyes in the textile industry. The successful application of the dye under both acidic and alkaline conditions makes it versatile for use in polyester dyeing, potentially reducing chemical waste and health risks associated with synthetic dyes.

Originality/value – This study contributes to the growing body of research on sustainable textile dyeing by demonstrating the potential of a coumarin-derived dye for polyester fabrics. Its fluorescence, non-toxic nature, robust fastness properties, eco-friendliness and adaptability to different dyeing conditions make it a valuable alternative to traditional hazardous dyes, supporting the shift toward greener practices in the textile industry.

Keywords Knoevenagel reaction, Eco-friendly dyeing, Coumarin dye, Polyester

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1. Introduction

Textile dyes are among the most persistent and harmful pollutants in industrial wastewater, contributing significantly to high biochemical oxygen demand and chemical oxygen demand (Lellis *et al.*, 2019; Katheresan *et al.*, 2018). Even small amounts of dyed fabric can release toxic chemicals into waterways, harming aquatic life and affecting human health in nearby communities (Khan and Malik, 2013; Donkadokula *et al.*, 2020).

These dyes are classified into various categories — including reactive, direct, basic, acidic – each with unique chemical properties that influence their behavior in water (Chequer *et al.*, 2013). Reactive dyes, for example, form strong covalent bonds with fibers, making them difficult to remove during treatment. Polyester, due to its hydrophobic and crystalline structure, is typically dyed with disperse dyes under high temperature and pressure. These dyes often contain poorly biodegradable compounds and require carriers and dispersants that intensify environmental damage (Lellis *et al.*, 2019).

Beyond ecological harm, textile dyes can be toxic, mutagenic and carcinogenic (Singh and Chadha, 2016). Some dyes bioaccumulate in the food chain, posing long-term health risks. Azo dyes, widely used in the industry, are especially concerning, with 15–50% failing to bind to fabric and ending up in wastewater (Lellis *et al.*, 2019). In many developing regions, untreated dye effluents are often reused for agriculture, amplifying the exposure. Workers in dye factories and residents near contaminated water sources face risks of skin diseases, respiratory issues and cancer, often exacerbated by weak environmental regulations and limited healthcare access (Kant, 2012; Norarmi *et al.*, 2022). Given the toxicity and environmental persistence of synthetic dyes, there is a growing push for safer alternatives. Natural dyes – derived from plants, minerals and animals – are generally biodegradable and less toxic (Yadav *et al.*, 2023). However, they often have weaker color intensity and lower fastness, and may require metallic mordants like chromium or aluminum, which themselves pose environmental risks (Samanta, 2018; Li *et al.*, 2022).

Among emerging alternatives, coumarins offer a promising solution. These naturally occurring compounds, found in many plants, have antimicrobial, fluorescent and coloring properties (Hussain *et al.*, 2019; Stefanachi *et al.*, 2018). Their chemical structure allows for versatile modifications to enhance dye performance. Coumarins exhibit strong UV–visible (UV–Vis) absorbance and can be structurally tuned to produce a range of hues by incorporating electron-donating groups (Sarmah *et al.*, 2021). They are also valued in industrial applications as fluorophores and chromophores, expanding their utility beyond textiles (Cazin *et al.*, 2020; Singh and Sheikh, 2022). Coumarin-based dyes combine strong color properties with excellent fastness and low toxicity, making them suitable for eco-friendly dyeing, especially for polyester – the most widely used synthetic fiber worldwide (Markandeya *et al.*, 2017). Conventional disperse dyes for polyester contain harmful aromatic amines and require auxiliary chemicals that contaminate water (Sharma *et al.*, 2021). Hence, identifying alternative dyes that eliminate hazardous carriers while maintaining performance is a critical step toward sustainable textile manufacturing.

This study investigates the synthesis and application of 7-diethylamino-3-acetylcoumarin, a coumarin-derived dye prepared via the Knoevenagel condensation reaction. The dye was applied to polyester fabric under varying pH conditions, with a focus on dye fixation and fastness properties. Reductive washing was evaluated for its effect on performance. Structural analysis was conducted using Fourier transform infrared spectroscopy, UV–Vis and NMR spectroscopy, whereas thermogravimetric analysis (TGA) assessed thermal behavior. Density functional theory (DFT) simulations were employed to understand dye–fiber interactions at the molecular level. In addition, *in vitro* cytotoxicity was tested using human skin fibroblast cells to confirm the dye's safety. The study presents a comprehensive evaluation of a structurally tunable, biodegradable dye as a viable alternative to toxic synthetic dyes in polyester applications.

2. Materials and methods

2.1 Materials

The study used 100% bleached polyester knitted fabrics (raschel warp knit, 255 g/m^2). The synthesized coumarin dye served as the colorant. Chemicals included acetic acid (CH_3COOH) and sodium hydroxide (NaOH) from Merck, and Dispersogen P Liquid from Clariant. For cytotoxicity testing, MTT (3–(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) and dimethyl sulfoxide (DMSO) were sourced from Sigma Aldrich (USA). Human skin fibroblast cells (CCD-1079Sk; CRL-2097) were obtained from the American Type Culture Collection (ATCC).

2.2 Methods

2.2.1 Synthesis

4-(Diethylamino)salicylaldehyde (2.00 g, 10.35 mmol) and ethyl acetoacetate (1.68 g, 12.94 mmol) were combined in 25 mL of ethanol. To this mixture, 1 mL of piperidine was added. The reaction was refluxed and stirred for 4 h, resulting in the precipitation of a yellow solid. After completion of the reaction, the mixture was filtered and the solid was washed with water. The crude product was then recrystallized from ethanol. The final product was a yellow solid with a yield of 97%. The reaction pathway is illustrated in Supplementary Figure 1.

2.2.2 Dyeing procedure

Polyester fabrics were dyed using a conventional exhaustion method at 135°C in a high-temperature dyeing machine (Roaches). To address the dye's water insolubility, 1.5 g of coumarin was pre-dissolved in 500 mL ethanol before bath preparation. Dyeing was conducted under both acidic and alkaline conditions (Table 1). Each 5 g sample was dyed at a liquor ratio of 1:40 for 45, 60, or 90 minutes.

Following dyeing, all polyester fabrics were sequentially rinsed with hot and cold water. Only select samples were then subjected to reductive washing, using a solution of 2 g/L sodium dithionite, 2 g/L sodium hydroxide, and 2 g/L wetting agent at 70°C for 20 minutes. Samples were then air-dried.

All dyeing procedure was performed in a high-temperature dyeing machine (Roaches) at 135°C under the following two conditions (Supplementary Figure 2):

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Table 1 Dyeing recipe of polyester fabric with coumarin dye

Material	Dyeing process Acidic	Alkaline
Material (g)	5	5
Liquor ratio	1:40	1:40
Coumarin (%)	1	1
Dispersogen P liquid (%)	1	1
Acetic acid (CH_3COOH) (g/L)	0.1	–
Sodium hydroxide (NaOH) (g/L)	–	0.1
Temperature (°C)	135	135
Time (min)	45, 60, 90	45, 60, 90
pH	5.5–6	8–9

Source(s): Authors' own work

1 *Acidic condition:* The dye bath contained coumarin dye, acetic acid (CH_3COOH) and a dispersing agent. Dyeing was conducted for 45, 60 or 90 minutes.
2 *Alkaline condition:* The dye bath included coumarin dye, sodium hydroxide (NaOH) and a dispersing agent. Dyeing was also carried out at 135°C for 45, 60 or 90 minutes.

After dyeing, all samples were rinsed with hot and cold water. Only selected samples, as indicated in Supplementary Table 1, underwent reductive washing using a solution of 2 g/L sodium dithionite, 2 g/L sodium hydroxide and 2 g/L wetting agent at 70°C for 20 min (liquor ratio: 1:40). After treatment, the bath was drained and fabrics were dried at room temperature.

2.2.3 Analysis

2.2.3.1 Characterization. An ORTHOLUX II POL-MK microscope was used under both visible and UV light to examine dyed polyester fabrics. FTIR analysis was conducted with a Perkin Elmer Spectrum 65 and a Shimadzu AIM-9000 Micro-FTIR. The chemical structure of the synthesized dye was confirmed using ^{1}H-NMR spectroscopy on a Bruker Avance III 500 MHz three-channel NMR spectrometer.

2.2.3.2 Color fastness properties. Colorfastness tests were performed following ISO standards: ISO 105-C06 for washing fastness, ISO 105-X12 for rubbing fastness and ISO 105-B02 for light fastness under a D65 artificial daylight source. The grayscale rating system (1 = worst, 5 = best) was used for washing and rubbing fastness, whereas the blue wool scale (1 = worst, 8 = best) was applied to assess light fastness.

2.2.3.3 Color measurement of dyed polyester fabric. Color characteristics were measured using a Datacolor SF600+ spectrophotometer with SAV aperture and SI mode. CIELab coordinates were recorded under D65/10° illumination/observer settings to quantify color values and differences.

2.2.3.4 Cell viability. The effect of the 7-diethylamino-3-acetylcoumarin dye on cell viability was determined using the *in vitro* MTT test. For this, human skin fibroblast cells CCD-1079Sk were seeded to 96-well transparent plates for 1×10^4 cells/well. The seeded cells were incubated for 24 h. The cells were then exposed to different concentrations of the 7-diethylamino-3-acetylcoumarin dye (0.015–1 mg/mL) for 24 h. 0.1% DMSO was used as a control. Then 10 μL per well of 5 mg/mL MTT solution was sieved into the wells and incubated at 37°C for 4 h. After incubation, the medium from the wells was aspirated and 100 μl of DMSO was added to each well. The plate was incubated for 20 min and then measured at 570 nm with a multimode reader (Synergy HTX, BioTek, USA). While the viability percentage values of the control cells were calculated as 100, the values of the other groups were compared with the control cells, and the viability percentages between the groups were compared. All experiments were repeated four times.

2.2.3.5 Ultraviolet–Visible absorbance, transmittance and thermal analysis. UV–Vis spectroscopy involves passing UV–Vis light through a sample and measuring the sample's transmittance of light. Absorbance may be computed from transmittance (T) using the formula A=-log(T). Electronic absorption spectrum in ethanol was recorded on Shimadzu UV-1800 UV–Visible Spectrophotometer. Absorbance and transmittance spectra of polyesters were also measured with M284D SDL ATLAS, Labsphere Transmittance Analyzer device. Fluorescence excitation and emission spectra were recorded on the Hitachi F-7000 spectrofluorometer. The thermal stability of coumarin dye and polyester was evaluated using TGA performed on a Perkin Elmer 4000 instrument. The measurements were carried out under a nitrogen atmosphere over a temperature range of 30–700°C, with a constant heating rate of 20°C min^{-1}.

2.2.3.6 Molecular modeling. To determine the approximate location and intermolecular interactions of the 7-diethylamino-3-acetylcoumarin dye on the polyester surface, it was calculated by the DFT method using B3LYP/6-31G(d,p) basis set with Gaussian16 software (Gaussian *et al.*, 2016). CYLview20 software was used for visualizations.

3. Results and discussion

3.1 Microscopy

Microscopy analysis revealed successful dyeing of polyester fabric under both acidic and alkaline conditions (Figure 1). The fabrics exhibited the expected color and fluorescent properties. Dyeing under acidic conditions demonstrated superior results for polyester fabric and coumarin.

3.2 Color values

CIELab measurements are summarized in Supplementary Table 2. Samples dyed under acidic conditions and subjected to reductive washing (e.g., A45R, A60R) exhibited more vivid color characteristics, with increased L*, b* and C* values indicating brightness and chroma.

3.3 Evaluation of fastness properties

Table 2 displays the results of staining and color change assessments on polyester fabrics following washing fastness tests. The results indicated that dyeing under acidic conditions improved the fastness of coumarin to the polyester significantly, especially after reductive washing. This performance surpassed that of fabrics that did not undergo reductive washing.

The most favorable outcomes were achieved when dyeing occurred in an acidic environment for 45 min, followed by reductive washing. While alkaline conditions also yielded good results, the combination of a 45-minute dyeing process and reductive washing consistently provided the best performance.

Figure 1 Microscope images (normal and UV light) of polyester fabric fabrics with different conditions

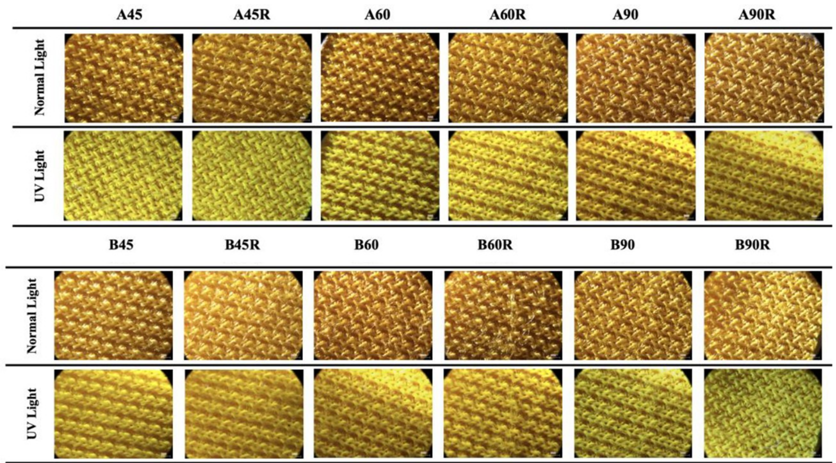

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Table 2 Washing fastness properties of the coumarin dye with different conditions on polyester fabric

Samples	Color changes	Color staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
A45	4	4–5	5	4–5	5	5	4–5
A45R	5	5	5	5	5	5	5
A60	3	4–5	5	4–5	5	5	4–5
A60R	4–5	5	5	4–5	5	5	4–5
A90	3–4	4–5	4–5	4–5	5	5	3
A90R	4	5	5	4–5	5	5	4–5
B45	3–4	5	5	5	5	5	4
B45R	4–5	5	5	5	5	5	4–5
B60	2–3	4–5	5	4–5	5	5	3–4
B60R	4	5	5	5	5	5	4–5
B90	3–4	4	4–5	3–4	5	5	3
B90R	4–5	4–5	5	4–5	5	5	4–5

Source(s): Authors' own work

In terms of staining, the 45-minute dyeing process followed by reductive washing produced the most satisfactory results for both acidic and alkaline conditions. These findings suggest that a 45-minute dyeing process in an acidic environment, followed by reductive washing, is the optimal method for achieving superior results.
According to the light fastness evaluation, results were recorded after 12 and 48 h. The sequence A45R yielded the best results, followed by A45, A60R, B45R and B90R. A45R demonstrated the highest resistance to both dry and wet rubbing, followed by A60R, B90R and A45, as seen in Table 3.

3.4 Optical properties and stability under light and thermal conditions

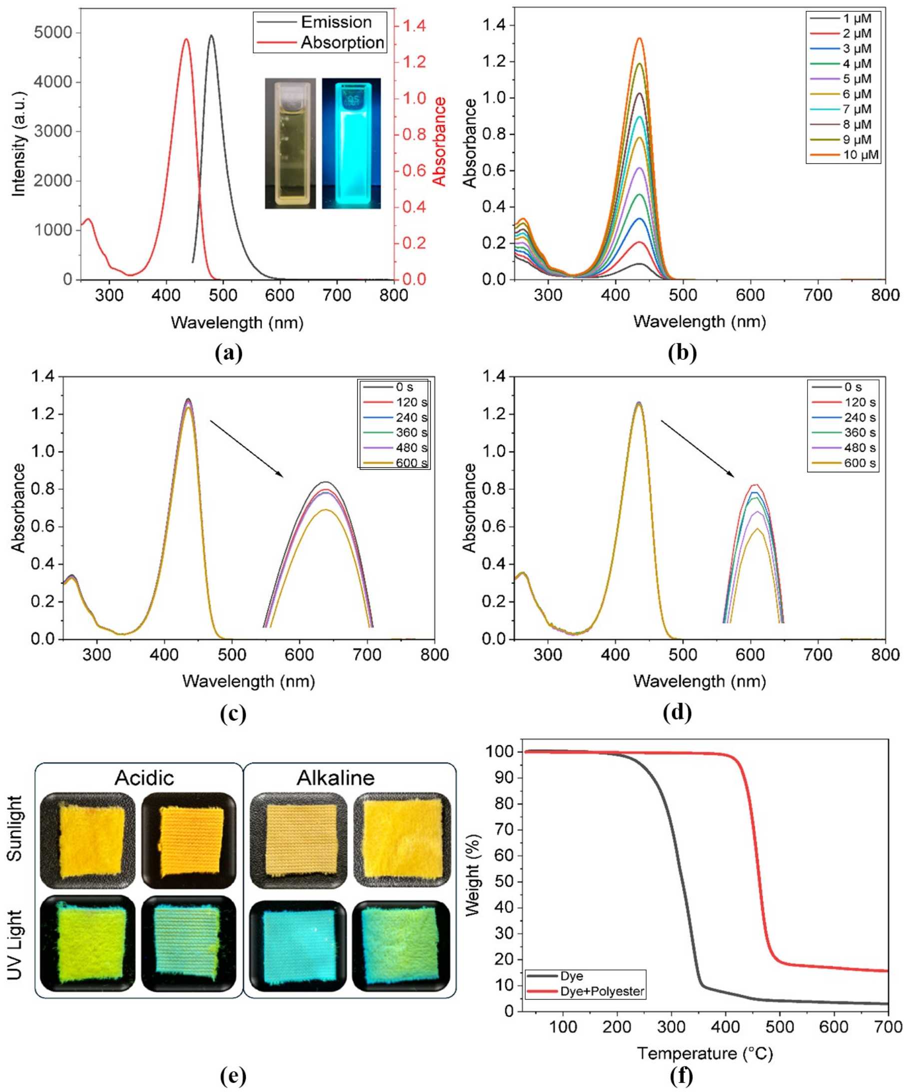
A band at 435 nm was observed in the UV–Vis spectrum of 7-diethylamino-3-acetylcoumarin dye at a concentration of 10 μM in ethanol. Fluorescence emissions in the ethanol are 479 nm and the Stokes shift is 44 nm (Figure 2). To investigate the aggregation behavior or concentration-dependent changes

Table 3 Light and rubbing fastness properties of the coumarin dye with different conditions on polyester knitting fabric

Samples	Light fastness		Rubbing fastness	
	12 h	48 h	Dry	Wet
A45	4–5	3–4	4–5	4
A45R	5–6	4–5	5	4–5
A60	4	3	4	4
A60R	5	3–4	4–5	4–5
A90	4–5	3–4	3	3
A90R	4–5	4	4	4
B45	4–5	3	4	3–4
B45R	5	3–4	4–5	4
B60	4	3	3–4	3–4
B60R	4–5	3–4	4	4
B90	4–5	3	4	4
B90R	5	4	4–5	4–5

Source(s): Authors' own work

Figure 2 (a) Absorbance and emission spectra of 7-diethylamino-3-acetylcoumarin in ethanol. (b) UV–Vis absorption spectra of 7-diethylamino-3-acetylcoumarin at different concentrations. (c) Absorption changes of 7-diethylamino-3-acetylcoumarin under 150 W daylight irradiation over 10 min. (d) Absorption changes of 7-diethylamino-3-acetylcoumarin under 150 W 366 nm UV light irradiation over 10 min. (e) Appearance of polyester dyed with acidic and alkaline coumarin under daylight and UV light. (f) Thermogravimetric analysis (TGA) curves of coumarin dye and coumarin-coated polyester



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of the coumarin compound, UV–Vis measurements were performed in ethanol at 10 different concentrations (1–10 μM). The 7-diethylamino-3-acetylcoumarin dye exhibited similar absorption characteristics at all concentrations, with no observable changes. Photodegradation studies were conducted to assess the stability of the coumarin compounds. The coumarin dye was exposed separately to 150 W daylight and 150 W 366 nm UV light for 10 min, and the changes in absorbance were monitored. After 10 min of irradiation, slight degradations and decreases were observed in the absorption band at 435 nm. This indicates that while the coumarin compound is resistant to intense light, it undergoes degradation over time (Figures 2c and d).

The thermal stability of coumarin dye and coumarin-coated polyester was evaluated by TGA, and the corresponding weight loss curves are presented in Figure 2f. All measurements were carried out under a nitrogen atmosphere to prevent oxidative degradation. The neat coumarin dye began to degrade at around 13°C and exhibited a single-step decomposition profile with a sharp weight loss observed in the temperature range of approximately 250–350°C. This temperature range corresponds to the rapid and extensive breakdown of the dye's organic structure. The total weight loss exceeded 97%, with a minimal residual mass (~3%) remaining above 400°C. This indicates that the dye is composed of thermally unstable organic components that degrade almost completely at elevated temperatures. In contrast, the coumarin-coated polyester sample exhibited significantly higher thermal stability. Negligible weight loss was recorded up to 400°C, suggesting that the material is resistant to thermal degradation at moderate temperatures. The main decomposition stage occurred between 400 and 500°C, which correspond to the typical thermal degradation range of the polyester backbone. In addition, a residual mass of approximately 15% was observed at 700°C, indicating the formation of carbonaceous residues derived from the polymer matrix. The distinct difference in thermal behavior between the two systems suggests that coating polyester with coumarin dye does not impart significant thermal resistance to the structure. While TGA analysis provides insight into the dye's thermal decomposition profile, it does not directly inform its behavior in aquatic environments. However, based on the dye's structure – lacking halogenated groups, azo linkages or heavy metals – it is expected to exhibit more favorable degradation pathways compared to conventional disperse dyes. The presence of electron-rich aromatic and carbonyl groups may promote photodegradation under UV exposure, whereas the low molecular weight and absence of persistent moieties suggest a higher likelihood of microbial degradation. These hypotheses warrant further investigation through simulated aquatic degradation studies to better assess the dye's environmental persistence and safety.

Solid UV–Vis measurements taken after dyeing polyester showed changes in absorbance and transmittance in the range of 250–450 nm. While pure polyester absorbs in the 300–375 nm range, the absorption band broadened upon dyeing, resulting in a visible difference. No significant differences were observed between acidic and alkaline dyeing conditions. Dyeing at lower temperatures resulted in relatively higher absorption above 375 nm compared to higher temperatures, suggesting slight degradation of coumarins at higher temperatures (Figure 3). When examining the transmittance spectra, undyed polyester transmitted light above 300 nm, whereas the coumarin-dyed polyesters absorbed light above 300 nm. These results indicate that the coumarin dyestuff is very effective in absorbing or desorbing light even at low concentrations.

3.5 Fourier transform infrared spectroscopy

The FTIR spectrum of the 7-diethylamino-3-acetylcoumarin dye showed an aromatic C–H peak at 3038 cm^{-1}. Aliphatic C–H peaks were observed at 2966–2871 cm^{-1}. Due to the presence of two carbonyl subgroups, the carbonyl band was split into two peaks at 1721 and 1714 cm^{-1}. C = C multiple bands were observed in the range of 1611–1501 cm^{-1}. For polyester, aliphatic C–H peaks were at 2971–2883 cm^{-1} and the C = O peak appeared as a sharp peak at 1714 cm^{-1}. The C–O stretching (ether band) was observed at 1095 cm^{-1}. Because the coumarin dyestuff was used at very low concentrations, no additional coumarin peaks were observed in the polyester-coumarin FTIR spectra, and a similar spectrum was obtained for all dyeing samples. The spectra were categorized as acidic and alkaline in Figure 4 and compared with each other.

When comparing the micro-FTIR measurements at 25 μm with the FTIR spectra, the target peaks were again displayed, and the results were consistent with each other as expected (Supplementary Figure 3).

Figure 3 Solid absorbance and transmittance spectra of acidic and alkaline polyester-coumarin textile products

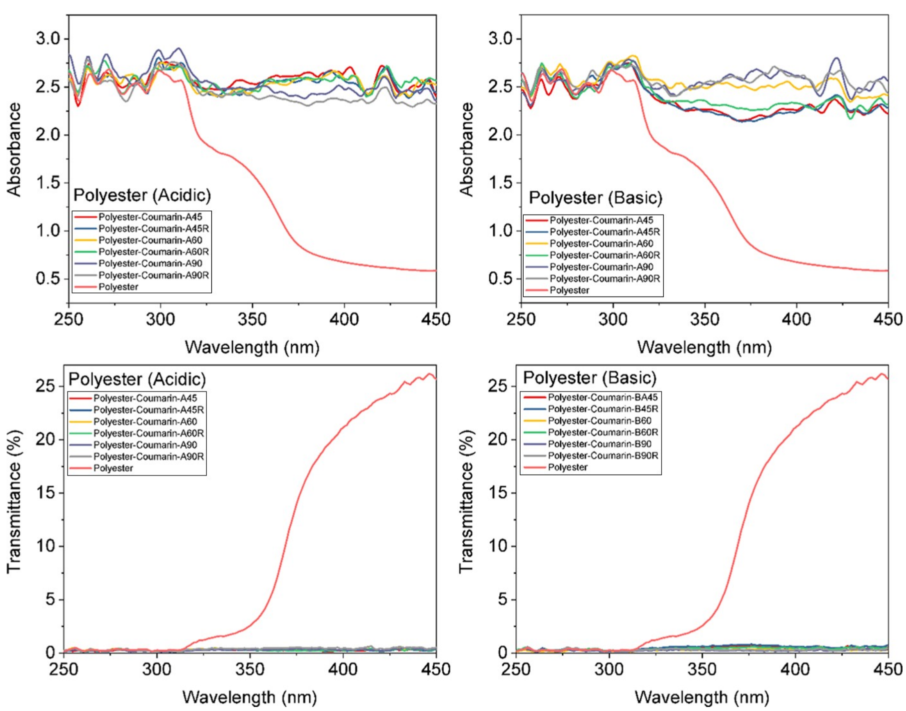

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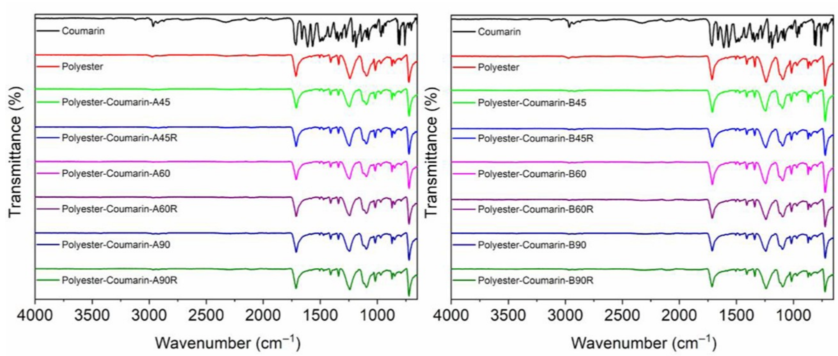
Figure 4 The FTIR spectra of 7-diethylamino-3-acetylcoumarin, polyester and coumarin dyed polyesters in acidic and alkaline conditions (A45-A90R and B45-B90R)



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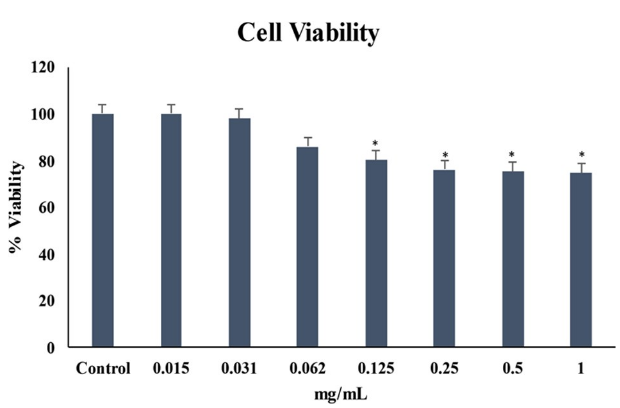
3.6 Cell viability

The CCD-1079Sk cells were incubated for 24 h with varying concentrations of the 7-diethylamino-3-acetylcoumarin dye to evaluate the effectiveness of the cell viability. After incubation, increasing doses of the dye in Figure 5 have been shown to have no cytotoxic effect on the cell. This study has similarities with literature. In a study investigating chormenoquinoline-based coumarin dye as a coumarin derivative, the cytotoxic effect of this derivative increasing dose in the HeLa cell line was evaluated. As a result, it was found that this dye did not show toxicity in cells up to 5 μM concentration (Tian *et al.*, 2022). However, three different coumarin derivatives were evaluated on Hs 613.sk human skin fibroblast cell line. It has been revealed that coumarin derivatives show toxicity depending on the dose increase at five different concentrations between 0 and 500 μM, especially at doses above 100 μM (Finn *et al.*, 2004). Xia *et al.* (2018) have shown that the coumarin-conjugated dye also showed no toxicity on HeLa cells exposed to different concentrations of the dye (2, 5, 10, 15 and 20 μM) for 48 h.

Figure 5 Effect of 7-diethylamino-3-acetylcoumarin dye on cell viability. The determination of cell viability was analyzed by the MTT test. According to the control, % cell viability was figured out by normalizing. The consequence of all experiments was given as the mean ± SD. (*p <0.05 is considered statistically significant)



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3.7 Theoretical modeling

The positioning of 7-diethylamino-3-acetylcoumarin on the polyester surface, as modeled by the DFT method, is significantly influenced by intermolecular interactions. The functional groups present on the coumarin molecule, such as the diethylamino and acetyl groups, tend to engage in hydrogen bond interactions with the polyester surface. These interactions play a crucial role in determining the stability and orientation of the coumarin molecule on the polyester substrate.

The distance between the coumarin group and the polyester structure is a critical factor in these interactions. The observed C–H···O = C hydrogen bond, with a length of 2.182 Å, indicates a strong and stable interaction (Supplementary Figure 4). This short bond length suggests a robust hydrogen bonding network that enhances the adhesion of the coumarin molecule to the polyester surface. In addition, the oblique angle at which the coumarin molecules are oriented relative to the polyester structure facilitates potential π-π interactions. These interactions, which occur between the aromatic rings of the coumarin and the polyester, further contribute to the overall stability and binding efficiency of the coumarin on the polyester surface. The combination of hydrogen bonding and π-π interactions ensures a strong and durable attachment of the coumarin dye to the polyester, which is essential for its application in dyeing processes.

Theoretical modeling based on DFT calculations revealed that the nitrogen atom on the diethylamino group and the carbonyl and ether oxygen atoms on the lactone ring significantly contribute to the dye-polyester interactions through hydrogen bonding and π–π stacking. In contrast, terminal methyl groups engage in weak van der Waals interactions with the polyester surface. Therefore, it is hypothesized that modifications involving functionally active groups prone to intermolecular interactions could enhance binding affinity and fastness properties by promoting stronger non-covalent interactions with the polyester substrate.

4. Conclusion

This study presents 7-diethylamino-3-acetylcoumarin as a promising, environmentally friendly dye for polyester fabrics. Synthesized via Knoevenagel condensation, the dye showed strong performance in colorfastness tests – particularly under acidic conditions with reductive washing – demonstrating resistance to washing, rubbing and light exposure. UV–Vis and fluorescence analyses confirmed its stable optical properties, whereas TGA results revealed thermal degradability, indicating low risk of environmental persistence during high-temperature treatments.

Importantly, cytotoxicity tests using human skin fibroblast cells confirmed that the dye is non-toxic, reinforcing its suitability for safer consumer and workplace applications. Molecular modeling provided insight into strong hydrogen bonding and π–π interactions with polyester fibers, supporting its effective adhesion and durability.

Although aquatic degradation pathways were not experimentally assessed, the dye's non-halogenated structure and absence of carcinogenic amines suggest a reduced ecological footprint compared to conventional disperse dyes. Future studies should explore aquatic breakdown behavior, compatibility with other textile types, and scalability for industrial use, contributing to broader adoption of sustainable dyeing practices in the textile industry.

Data availability

Data will be made available on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

The supplementary material for this article can be found online.

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