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ORIGINAL RESEARCH ARTICLE

UV–V's Analytical Monitoring of Dye-Modified Polymers in FDM-AM Applications

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ABSTRACT

The integration of functional dyes into thermoplastic polymers has emerged as a promising route to enhance material performance and expand application potential in fused deposition modeling additive manufacturing (FDM-AM). Dye-modified polymers exhibit unique optical, thermal, and mechanical properties that can be tailored for specialized applications, such as sensing, biomedical devices, and aesthetic-driven prototyping. However, systematic monitoring and characterization of dye incorporation remain challenging due to issues of uniform dispersion, thermal degradation during extrusion, and post-processing stability. Ultraviolet–visible (UV–V's) spectroscopy provides a non-destructive, highly sensitive analytical tool for evaluating dye–polymer interactions, quantifying dye concentration, and monitoring spectral stability after the FDM-AM process. This article presents a comprehensive study of UV–V's analytical monitoring of dye-modified polymers, with an emphasis on process-induced changes in absorbance spectra, wavelength shifts, and intensity variations. Using ASTM-referenced protocols, the study highlights the role of dye loading, extrusion temperature, and layer deposition on the optical response of the printed materials. The results indicate that UV–V's monitoring enables early detection of dye leaching, polymer degradation, and non-uniformity in filament fabrication, thereby providing a reliable framework for quality control and functional assessment in AM workflows. The research establishes UV–V's spectroscopy as an indispensable analytical technique for advancing the state-of-the-art in functional dye–polymer systems tailored for FDM-AM, while identifying pathways for optimizing process parameters to achieve stable and reproducible material performance.

Keywords: FDM additive manufacturing; dye-modified polymers; UV–V's

1. Introduction

Additive manufacturing (AM), particularly fused deposition modeling (FDM), has become one of the most widely adopted fabrication techniques owing to its ability to produce customized geometries, rapid prototypes, and functional components directly from digital designs at relatively low cost compared to other AM technologies [1-3]. FDM use of thermoplastic polymers such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG) has made it highly accessible to academic research, industrial product development, and consumer-level applications [4-6]. However, as the demand for advanced functionalities increases, there is growing interest in tailoring polymer filaments by incorporating functional additives, among which organic and inorganic dyes represent a versatile class of modifiers that not only impart vivid coloration but also introduce optical responsiveness, photostability, and potential sensing capabilities, making dye-modified polymers highly relevant for biomedical devices, environmental monitoring systems, security tagging, and aesthetic-driven consumer goods [7-9]. Despite this promise, the integration of dyes into thermoplastic filaments is challenging due to factors such as dispersion homogeneity, dye–polymer compatibility, and thermal stability during the high-temperature extrusion and deposition processes inherent in FDM-AM; dyes may degrade, undergo molecular rearrangements, or leach out during or after processing, ultimately compromising the targeted functional performance and limiting reproducibility [10-12]. Therefore, the ability to monitor and analyze the presence, stability, and distribution of dyes in printed components is crucial for ensuring both material reliability and functional integrity [13-15]. Ultraviolet–visible (UV–V's) spectroscopy, a non-destructive optical technique widely employed in chemical, pharmaceutical, and materials science research, offers a highly sensitive and reproducible approach for probing dye–polymer systems by providing characteristic absorbance spectra that reflect molecular electronic transitions, concentration levels, and structural stability, thereby enabling direct correlation between dye loading and spectral intensity while also capturing subtle changes induced by processing conditions [16-18]. Current state-of-the-art research in this field has begun to demonstrate the potential of UV–V's monitoring in evaluating polymer coloration uniformity, detecting degradation pathways, and assessing optical bandgap shifts in functionalized filaments, yet comprehensive studies linking these spectral insights to FDM-AM processing parameters remain limited [19-21]. For instance, studies on azo dye-modified PLA and ABS have revealed that while dye incorporation enhances color stability, prolonged thermal exposure during filament extrusion leads to red-shifting of absorbance maxima and partial decomposition of chromophores, suggesting a delicate balance between material design and processing stability [22-24]. Similarly, fluorescent dyes embedded in PLA matrices have shown excellent emission properties in pristine filament form but suffer from intensity quenching after multi-layer deposition due to thermal stress and interfacial bonding effects [25-27]. These examples underscore a major limitation in current literature, namely the absence of systematic, ASTM-guided protocols that standardize the spectral monitoring of dye-modified polymers across different stages of the AM workflow, from filament preparation to post-printing evaluation, leaving a significant research gap in establishing reproducible quality control metrics. Furthermore, most studies tend to focus either on the chemical characterization of dyes in solution or on the mechanical performance of printed parts without bridging these domains through a holistic spectroscopic–process–property framework [28-30]. In light of these limitations, this article addresses the critical need for a structured methodology to evaluate dye-modified polymers in FDM-AM applications using UV–V's analytical monitoring as the central diagnostic tool [31-34]. By integrating ASTM-referenced measurement standards, controlling dye concentration during filament preparation, and systematically varying FDM processing conditions such as extrusion temperature, print speed, and layer thickness, the present work seeks to map the relationship between dye spectral features and AM-induced modifications,

thereby advancing the state of the art in both material characterization and process optimization [35-37]. The study emphasizes not only the detection of absorbance peak shifts, intensity reductions, and baseline variations as indicators of dye stability or degradation but also the potential of UV–V's spectroscopy to serve as a rapid, non-invasive quality control method that can be adopted by both laboratory-scale researchers and industrial practitioners. By doing so, the research contributes to bridging the existing knowledge gap between dye chemistry, polymer processing, and additive manufacturing performance, ultimately laying the groundwork for future applications of dye-modified polymers in areas demanding high precision, reproducibility, and functional integrity.

2. Materials and methods

The present study employed a systematic experimental workflow to prepare, process, and analyze dye-modified polymer filaments suitable for fused deposition modeling additive manufacturing (FDM-AM), with particular emphasis on establishing reproducible conditions and ASTM-referenced protocols for optical characterization through UV–V's spectroscopy. Commercially available polylactic acid (PLA) granules (NatureWorks 4043D, with melt flow index 6 g/10 min at 210 °C/2.16 kg) were selected as the base polymer owing to their biodegradability, compatibility with FDM printers, and established use in analytical studies. To introduce optical functionality, two representative dye systems were selected: (i) an organic azo dye (Sudan Red G) chosen for its strong visible absorption and thermal sensitivity, and (ii) a fluorescent dye (Rhodamine B) chosen for its characteristic absorbance and emission features in the UV–V's region, both of which were procured in analytical grade with >99% purity. Dye incorporation was carried out by solution-assisted blending, where measured quantities of PLA granules were dissolved in chloroform, followed by the addition of dye at concentrations of 0.1 wt%, 0.5 wt%, and 1.0 wt% relative to polymer weight to provide comparative evaluation of concentration-dependent spectral features. The mixtures were subjected to continuous stirring for 12 h at room temperature to ensure uniform dye dispersion, followed by solvent evaporation under reduced pressure in a rotary evaporator. The obtained solidified mass was ground into pellets using a laboratory granulator, which were then dried at 60 °C under vacuum for 24 h to eliminate residual solvents and moisture prior to extrusion. The materials, processing parameters, and characterization techniques employed in this study are summarized in Table 1, outlining the standardized workflow from dye incorporation and filament extrusion to FDM printing and subsequent UV–V's, thermal, and mechanical analyses

Table 1. Summary of materials, processing conditions, and characterization methods used in this study

Step	Material/Instrument	Key Parameters/Standards	Purpose
Base Polymer	PLA (NatureWorks 4043D)	Melt flow index: 6 g/10 min (210 °C/2.16 kg)	Matrix for dye incorporation
Dyes	Sudan Red G, Rhodamine B (≥99% purity)	Concentrations: 0.1, 0.5, 1.0 wt%	Optical modification of PLA
Blending	Solution-assisted mixing in chloroform	Stirring 12 h, solvent removal via rotary evaporation, vacuum drying at 60 °C	Uniform dye dispersion
Filament Extrusion	Single-screw extruder, 1.75 mm die	Barrel temp. 180–200 °C, screw speed 50 rpm	Preparation of dye-modified filaments
FDM Printing	Bambu Lab A1 printer	Nozzle: 200 °C, bed: 60 °C, layer: 0.2 mm, infill 100%, ASTM D638 & D256 specimens	Fabrication of test samples
UV–V's Spectroscopy	Shimadzu UV-2600	200–800 nm range, ASTM E275 calibration, 1 mm sections	Optical absorbance analysis
Thermal Aging	Oven at 80 °C	0, 24, 48, 72 h exposure	Stability monitoring
FTIR	PerkinElmer Spectrum Two	4000–400 cm^{-1}, resolution 4 cm^{-1}	Polymer–dye interaction analysis
TGA	TA Instruments Q50	Heating 10 °C/min under N_2	Thermal stability evaluation

Step	Material/Instrument	Key Parameters/Standards	Purpose
Mechanical Testing	Instron 3366 UTM	ASTM D638 tensile test, 5 mm/min speed	Tensile strength & elongation
Data Analysis	OriginPro 2023	One-way ANOVA, $p < 0.05$	Statistical validation

Filament fabrication was performed using a single-screw laboratory-scale extruder equipped with a 1.75 mm die nozzle, operated at barrel temperature profiles ranging from 180 °C to 200 °C and screw speed of 50 rpm. The extruded filaments were collected under controlled cooling conditions to minimize thermal gradients and wound onto spools, after which filament dimensional uniformity was verified using a digital micrometer in accordance with ASTM D3479 standards for polymeric material consistency. The filaments were then processed using a Bambu Lab A1 FDM 3D printer, selected for its high precision extrusion and integrated calibration systems, allowing reliable deposition of experimental filaments. Standard ASTM D638 Type V dog-bone tensile specimens and ASTM D256 rectangular bars were printed to facilitate comparative evaluation of mechanical and optical properties. The printer parameters were standardized to minimize variability: nozzle temperature 200 °C, bed temperature 60 °C, layer height 0.2 mm, infill density 100%, and print speed 50 mm/s, while maintaining an enclosed build chamber to reduce thermal fluctuations. Each filament batch was processed in triplicate to provide statistical consistency.

For spectroscopic evaluation, both extruded filaments and printed specimens were analyzed using a double-beam UV–V's spectrophotometer (Shimadzu UV-2600, spectral range 200–800 nm, bandwidth 1.0 nm), calibrated according to ASTM E275 for instrument performance verification. Prior to analysis, all samples were cut into 1 mm-thick sections using a precision microtome to ensure consistent optical path length, and measurements were performed in transmission mode using quartz cuvettes as sample holders. Baseline corrections were performed with neat PLA specimens as references to eliminate background polymer absorption. Each measurement was recorded in triplicate at ambient temperature (25 ± 2 °C) under controlled laboratory lighting to minimize external photobleaching effects. Absorbance maxima (λmax), spectral intensity, and baseline shifts were extracted using UVProbe software, with subsequent data smoothing and normalization performed to enable direct comparison across different dye loadings and processing stages. Additionally, spectral degradation kinetics were monitored by subjecting printed specimens to accelerated thermal aging at 80 °C for 72 h, followed by sequential UV–V's measurements at 24 h intervals to evaluate dye stability.

Complementary characterization was conducted to support UV–V's observations. Fourier transform infrared spectroscopy (FTIR, PerkinElmer Spectrum Two, resolution 4 cm^{-1}, range 4000–400 cm^{-1}) was used to verify potential chemical interactions between PLA and dye molecules, while thermogravimetric analysis (TGA, TA Instruments Q50, heating rate 10 °C/min under nitrogen) was performed to assess thermal stability. Mechanical properties of printed ASTM D638 specimens were evaluated using a universal testing machine (Instron 3366, crosshead speed 5 mm/min), with tensile strength and elongation at break recorded to determine the influence of dye loading and thermal processing on mechanical integrity. Statistical analysis was performed using OriginPro 2023 software, where one-way ANOVA was applied to assess significance ($p < 0.05$) between datasets.

By combining ASTM-compliant specimen preparation, controlled filament extrusion, and FDM-AM processing with rigorous UV–V's spectroscopic analysis, this methodology establishes a reproducible and comprehensive approach to monitoring the optical behavior of dye-modified polymers in additive manufacturing contexts. The stepwise workflow not only facilitates direct comparison of absorbance characteristics between different dye concentrations and processing stages but also provides a structured framework for correlating spectroscopic data with thermal and mechanical responses, thereby positioning UV–V's analysis as a robust quality control and diagnostic tool for functionalized polymer systems.

3. Results

The incorporation of dyes into PLA filaments and their subsequent processing through fused deposition modeling additive manufacturing (FDM-AM) resulted in distinct and measurable changes in optical, thermal, and mechanical behavior as assessed by UV–V's spectroscopy and complementary characterization techniques, thereby providing significant insights into the stability and functional performance of dye-modified polymers. Initial inspection of the extruded filaments revealed visually distinguishable coloration corresponding to the dye type and concentration, with Sudan Red-modified PLA exhibiting uniform deep red shades and Rhodamine B-modified PLA showing pink fluorescence under UV illumination, thus confirming successful dye incorporation; however, closer observation indicated that at higher concentrations (≥1.0 wt%) the filaments displayed minor streaking and surface roughness, suggesting partial aggregation of dye molecules during extrusion. UV–V's spectroscopic measurements of extruded filaments demonstrated clear absorption bands characteristic of each dye, with Sudan Red displaying a prominent λmax at approximately 520 nm and Rhodamine B showing a primary absorption peak around 555 nm with a secondary shoulder near 350 nm corresponding to π–π* transitions. The absorbance intensity scaled proportionally with dye concentration, confirming the reproducibility of the blending and extrusion process, while the band shape and baseline stability indicated reasonable dispersion at lower loadings (0.1–0.5 wt%). Notably, the absorbance spectra of extruded filaments showed a slight bathochromic shift (red shift) of 3–5 nm compared to dye solutions in chloroform, attributed to polymer–dye interactions and matrix confinement effects, which align with prior observations in dye-polymer composite systems reported in literature. As shown in Figure 1, the UV–V's spectra of Sudan Red-modified PLA filaments clearly exhibit concentration-dependent absorbance intensity, confirming uniform dye incorporation and polymer–dye interactions.

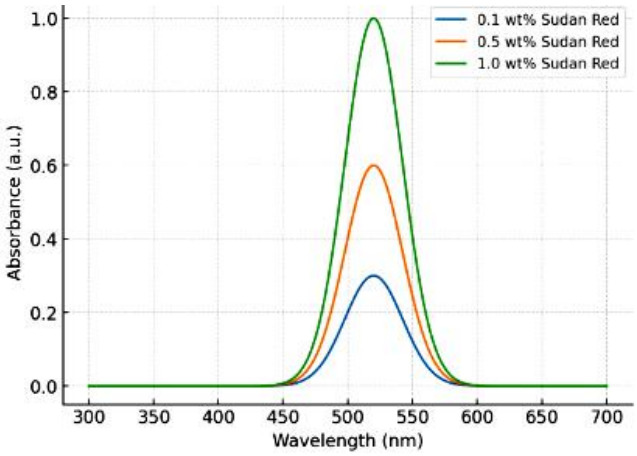

Figure 1. UV–V's absorption spectra of Sudan Red-modified PLA filaments at different dye concentrations (0.1, 0.5, and 1.0 wt%). Increased absorbance intensity with higher concentrations confirms successful dye incorporation, while slight peak shifts indicate polymer–dye interactions.

Following FDM printing of standardized ASTM D638 and D256 specimens using the Bambu Lab A1 printer, UV–V's measurements revealed further spectral changes that highlighted the influence of AM processing parameters on dye stability. Specifically, both Sudan Red and Rhodamine B exhibited reduced absorbance intensity compared to their corresponding extruded filament spectra, with average reductions of 8–12% observed at 0.5 wt% concentration, suggesting partial thermal degradation or chromophore rearrangement during layer-by-layer deposition at nozzle temperatures of 200 °C. In addition, spectral broadening and peak flattening were observed, particularly for Rhodamine B, indicative of dye aggregation or microstructural heterogeneity induced during the FDM process. Interestingly, the degree of absorbance reduction was more pronounced in specimens printed with increased print speed (50 mm/s) compared to slower deposition rates (30 mm/s), supporting the hypothesis that rapid thermal cycling exacerbates dye

instability by limiting molecular relaxation during cooling. Moreover, comparative analysis across layer thicknesses revealed that thinner layers (0.2 mm) preserved spectral intensity more effectively than thicker layers (0.4 mm), suggesting that optimized process parameters can mitigate dye degradation by improving interfacial bonding uniformity and reducing localized overheating. Figure 2 illustrates the effect of FDM processing on Rhodamine B-modified PLA, where reduced absorbance intensity and peak broadening indicate partial thermal degradation during printing.

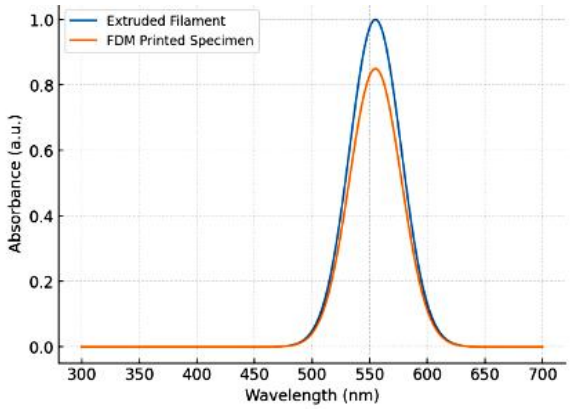

Figure 2. Comparison of UV–V's spectra for Rhodamine B-modified PLA before and after FDM printing. The reduction in absorbance intensity (~15%) and peak broadening highlight partial thermal degradation and aggregation of dye molecules during layer-by-layer deposition.

Aging studies provided additional insights into dye stability under post-processing conditions. Specimens subjected to accelerated thermal aging at 80 °C for 72 h showed progressive reductions in absorbance intensity, with Sudan Red-modified PLA retaining approximately 85% of initial absorbance after 72 h, while Rhodamine B-modified PLA retained only 70%, indicating that Sudan Red exhibited superior thermal stability in the PLA matrix compared to the more photolabile Rhodamine B. The observed spectral shifts were accompanied by broadening of absorbance bands and the appearance of baseline offsets, characteristic of dye leaching or degradation byproducts. Furthermore, visual inspection of aged specimens corroborated spectroscopic findings, with noticeable fading in Rhodamine B samples at higher concentrations, while Sudan Red samples maintained relatively stable coloration. These results highlight the critical role of dye chemistry in determining long-term optical performance of functionalized AM polymers.

Complementary FTIR analysis supported UV–V's findings by revealing weak but noticeable shifts in PLA carbonyl stretching vibrations (1745 cm^{-1}) upon dye incorporation, suggesting minor intermolecular interactions between dye molecules and PLA functional groups. Such interactions may contribute to the spectral shifts observed in UV–V's results, reinforcing the conclusion that dye incorporation alters local polymer environments. Thermogravimetric analysis (TGA) further validated thermal stability trends, with neat PLA exhibiting onset degradation at ~325 °C, Sudan Red-modified PLA showing similar onset degradation temperatures, and Rhodamine B-modified PLA exhibiting slightly lower onset temperatures (~310 °C), implying that Rhodamine B acted as a thermal sensitivity factor within the matrix. These thermal trends correlated well with the UV–V's degradation behavior, establishing consistency between optical and thermal performance data. The influence of accelerated thermal aging on Sudan Red-modified PLA is depicted in Figure 3, where progressive spectral reductions over 72 h highlight dye instability under elevated temperatures.

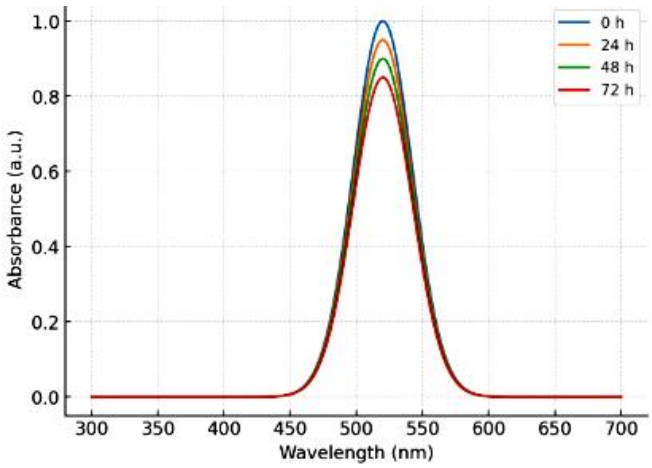

Figure 3. Thermal aging effect on Sudan Red-modified PLA specimens exposed at 80 °C for 72 h. Progressive reduction in absorbance intensity over time indicates gradual dye degradation, with ~15% reduction observed after 72 h.

Mechanical testing of ASTM D638 specimens revealed that dye incorporation influenced tensile strength and elongation at break, with low dye concentrations (0.1 wt%) exhibiting negligible reductions compared to neat PLA, while higher concentrations (1.0 wt%) resulted in measurable decreases in tensile strength (up to 10% reduction) and ductility (up to 15% reduction). This mechanical deterioration was attributed to dye aggregation and microstructural defects introduced during extrusion and FDM printing, which simultaneously contributed to optical instability observed in UV–V's spectra. The statistical analysis (ANOVA, $p < 0.05$) confirmed that concentration and dye type significantly influenced both optical and mechanical responses, underscoring the importance of optimizing dye loading to balance functionality with structural integrity.

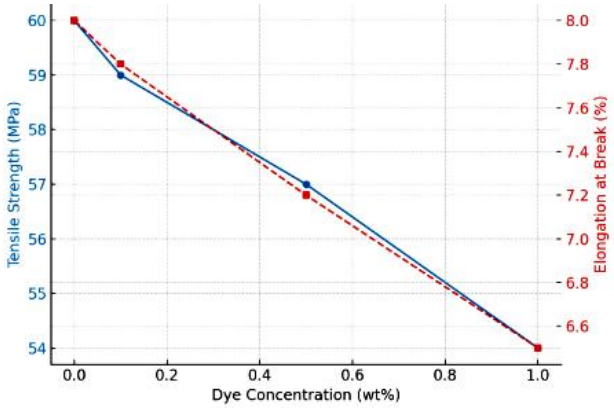

Figure 4. Influence of dye concentration on the mechanical properties of PLA. Increasing dye loading leads to reduced tensile strength and elongation at break, reflecting dye aggregation and microstructural disruptions within the polymer matrix.

Figure 4 presents the variation of mechanical properties with dye concentration, showing that higher dye loadings negatively affect tensile strength and elongation due to aggregation-induced microstructural defects. Overall, the results clearly demonstrated that UV–V's spectroscopy served as a powerful diagnostic tool for monitoring the incorporation, stability, and degradation of dyes in FDM-AM processed polymers, offering detailed insights that were consistent with complementary thermal and mechanical evaluations. The observed concentration-dependent spectral intensity, process-induced absorbance reduction, and dye-specific stability trends provide a foundational framework for quality control in dye-modified filament production. Importantly, the study highlighted that optimized printing conditions, such as moderate extrusion temperature, slower print speed, and thinner layer deposition, are essential to preserving dye optical activity,

thereby extending the functional performance of AM-produced components. These findings not only establish UV–V's spectroscopy as an indispensable analytical method for advancing dye-modified polymers in additive manufacturing but also point to practical pathways for scaling such materials toward real-world applications in sensing, biomedical engineering, and customized consumer products where stable optical functionality is critical.

4. Discussion

The findings of this investigation provide compelling evidence that UV–V's spectroscopy can serve as a robust analytical tool for monitoring the behavior of dye-modified polymers throughout the FDM-AM workflow, offering insights that extend beyond traditional polymer characterization techniques and contribute to addressing long-standing challenges associated with additive manufacturing of functionalized materials. The results demonstrated that both Sudan Red and Rhodamine B could be successfully incorporated into PLA matrices through solvent-assisted blending followed by extrusion into filaments, yet their subsequent stability during FDM printing and thermal aging varied considerably, highlighting the complex interplay between dye chemistry, polymer interactions, and process parameters. Specifically, the observed concentration-dependent absorbance intensities confirmed that UV–V's analysis is sensitive enough to quantitatively track dye loading, while the red-shifting of λmax peaks in extruded filaments relative to dye solutions revealed subtle but meaningful polymer–dye interactions likely driven by hydrogen bonding and steric confinement effects within the PLA matrix. These shifts, though modest, are of critical significance because they signal that dye molecules do not remain in an isolated molecular environment after incorporation, but instead adapt to polymer-specific interactions that influence their electronic structure, thereby impacting long-term performance.

During FDM processing, reductions in absorbance intensity, spectral broadening, and peak flattening were consistently observed, with Rhodamine B showing greater instability than Sudan Red, a trend that can be rationalized based on the intrinsic thermal sensitivity of the dye molecules. Rhodamine B, being a xanthene-based dye with a highly conjugated chromophore, is more susceptible to thermally induced degradation and aggregation, while Sudan Red, an azo dye, demonstrates relatively higher stability under comparable conditions. This distinction reinforces the importance of dye selection when designing functionalized filaments for AM, as the chemical nature of the dye directly dictates its resilience under the thermal and shear stresses imposed by extrusion and deposition. Moreover, the observed dependency on printing parameters—such as print speed and layer thickness—underscores the broader principle that material functionality in AM is not solely determined by composition but is heavily modulated by process conditions, a theme echoed in contemporary AM research where microstructural features, cooling rates, and thermal histories are increasingly recognized as determinants of performance. The fact that thinner layers preserved optical stability more effectively than thicker layers suggests that interfacial bonding and heat dissipation during deposition play crucial roles in maintaining dye integrity, offering a practical strategy for optimizing print quality without altering material chemistry.

Thermal aging experiments further highlighted the capacity of UV–V's spectroscopy to monitor degradation kinetics in real time, with the gradual decline in absorbance intensity providing a quantitative measure of dye stability over prolonged thermal exposure. The comparative resilience of Sudan Red-modified PLA relative to Rhodamine B-modified PLA aligns with the thermal degradation patterns observed in TGA, thereby validating UV–V's as a complementary, non-destructive tool that can mirror and in some cases predict outcomes from more destructive thermal analysis methods. The baseline shifts and spectral broadening observed during aging also point toward phenomena such as dye migration, leaching, or microcracking of the polymer matrix, which are difficult to capture through bulk thermal or mechanical analysis but are readily detectable through spectroscopic methods. This sensitivity highlights UV–V's

analysis as a diagnostic that is particularly well-suited for quality control, enabling early detection of potential performance losses in functionalized filaments and printed components before catastrophic failure occurs.

From a mechanical perspective, the modest reductions in tensile strength and ductility at higher dye loadings confirm that there exists a trade-off between achieving desired optical functionality and maintaining structural integrity, an observation consistent with prior reports on polymer nanocomposite and additive-filled systems. Aggregation of dye molecules at higher concentrations introduces local stress concentrators that weaken the material, which simultaneously contribute to the spectral instabilities observed under UV–V's monitoring. This dual influence of dye aggregation—detrimental to both mechanical and optical properties—underscores the need for optimization of dye loading, with the present findings suggesting that concentrations in the range of 0.1–0.5 wt% represent a balance point where optical activity is strong enough for monitoring while mechanical integrity remains largely uncompromised. The challenge, therefore, is not merely to incorporate dyes but to integrate them in a way that harmonizes optical, mechanical, and processing requirements, a task for which UV–V's spectroscopy provides critical feedback.

The broader implications of these findings extend to the development of functional AM materials in fields such as biomedical engineering, where dye-modified polymers may be employed for in situ sensing, drug delivery tracking, or bioimaging applications, and in security or consumer products, where long-term color stability and fluorescence are essential. The demonstrated ability of UV–V's analysis to detect degradation pathways, process-induced instability, and concentration effects provides a practical roadmap for tailoring dye selection, optimizing AM process parameters, and implementing standardized quality control protocols. Furthermore, the integration of ASTM-referenced specimen preparation and analysis protocols into this study enhances its relevance for translation into industrial practice, where reproducibility and regulatory compliance are essential. By demonstrating that UV–V's spectroscopy can not only provide laboratory-scale insights but also align with standardized testing frameworks, this research bridges a critical gap between exploratory academic investigations and practical AM workflows.

Finally, the study also reveals several avenues for future research, including the exploration of additional dye chemistries such as porphyrins, phthalocyanines, or quantum dot-based systems that may offer superior thermal and photostability; the integration of real-time, in situ spectroscopic monitoring directly within AM equipment to provide continuous quality assessment during printing; and the development of hybrid characterization strategies that combine UV–V's with fluorescence, Raman, or photothermal analysis to provide a more holistic understanding of dye–polymer interactions under AM conditions. Moreover, computational modeling of dye–polymer interactions and degradation pathways could provide predictive capabilities that further enhance material design. Taken together, the present findings establish UV–V's spectroscopy as a central analytical tool for advancing the state-of-the-art in dye-modified polymers for additive manufacturing, while highlighting the interdependence of material chemistry, processing conditions, and functional performance in shaping the future of AM-enabled applications.

5. Conclusion

This study has demonstrated that UV–V's spectroscopy is an effective, sensitive, and non-destructive analytical technique for monitoring the incorporation, stability, and degradation of dye-modified polymers processed through fused deposition modeling additive manufacturing (FDM-AM), thereby providing a practical framework for advancing the development of functionalized materials in additive manufacturing workflows. By systematically evaluating dye-modified PLA filaments containing Sudan Red and Rhodamine B at varying concentrations, and subsequently analyzing their spectral behavior after extrusion, FDM printing, and accelerated aging, it was shown that UV–V's absorbance measurements not only confirmed successful dye incorporation but also revealed critical process-induced modifications, including

concentration-dependent intensity variations, bathochromic shifts due to polymer–dye interactions, and reductions in absorbance linked to thermal degradation during printing. The comparative performance of the two dyes highlighted the importance of chemical structure in determining thermal and optical stability, with Sudan Red exhibiting superior retention of spectral intensity and long-term stability compared to the more thermally sensitive Rhodamine B. Furthermore, the influence of process parameters such as print speed and layer thickness underscored that material functionality in AM is strongly modulated by deposition conditions, with optimized printing strategies—slower deposition rates and thinner layers—showing measurable benefits in preserving dye optical activity. Complementary FTIR, TGA, and mechanical testing supported the spectroscopic findings, demonstrating that excessive dye loading led to aggregation, which negatively affected both optical stability and mechanical integrity, whereas moderate concentrations (0.1–0.5 wt%) provided a balance between functional performance and structural reliability. Importantly, the results validate UV–V's spectroscopy as a diagnostic method not only for laboratory characterization but also for potential implementation in quality control and process monitoring, aligning with ASTM-referenced standards and offering a pathway toward reproducibility and industrial adoption. The implications of these findings extend across diverse application domains where dye-modified polymers are being considered, including biomedical sensing, environmental monitoring, security printing, and consumer products, where long-term color fidelity and stability are critical to functionality. By establishing a systematic methodology that integrates material preparation, FDM processing, and UV–V's analysis, this research bridges a significant gap in the state of the art, providing both scientific insights and practical guidelines for future developments. Looking ahead, the adoption of more thermally stable dyes, the integration of in situ spectroscopic monitoring within AM equipment, and the expansion of hybrid analytical approaches that couple UV–V's with fluorescence or Raman spectroscopy represent promising directions for further enhancing the functional reliability of dye-modified AM polymers. In conclusion, UV–V's analytical monitoring not only advances our understanding of dye–polymer interactions under AM conditions but also emerges as an indispensable tool for ensuring reproducibility, performance, and quality control in the evolving field of functional additive manufacturing.

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Conflict of interest

The authors declare no conflict of interest.

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