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KEMENTERIAN PENDIDIKAN TINGGI



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A Sustainable Innovation for Enhanced Natural Dye Extraction and Dyeing

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ABSTRACT

The global textile industry is a major contributor to water pollution due to its reliance on toxic synthetic dyes. While natural dyes offer an eco-friendly alternative, conventional heat-based extraction methods degrade heat-sensitive pigments, consume high energy, and yield inconsistent dye particle sizes, leading to uneven coloration. This study aims to develop and investigate a high-efficiency, sustainable system for natural dye extraction and textile dyeing, specifically evaluating a technological approach against traditional methods. Using turmeric as the natural dye source, the extraction process involved four main techniques. The proposed innovation combined freeze-drying, homogenization, and sonication and was compared against the traditional direct boiling method. Findings revealed that the proposed technique drastically reduced the mean particle size to 1252.29 nm compared to the traditional technique (4853.75 nm), ensuring highly uniform dispersion. Furthermore, UV-Vis spectrophotometry demonstrated that proposed technique achieved the highest colour absorbance peak, far surpassing the traditional method. A visual assessment survey confirmed a 100% user preference for cotton fabrics dyed using the proposed technique due to superior brightness and evenness. In conclusion, the integration of freeze-drying, homogenization, and sonication resolves the traditional bottlenecks of natural dyes, significantly improving colour intensity and particle uniformity. This eco-friendly innovation eliminates the need for toxic heavy-metal mordants, minimizes energy consumption, and holds immense commercial potential for sustainable textile coloration towards a zero-carbon footprint.

Keywords: natural dye, freeze-dry, homogenation, sonication

1. INTRODUCTION

The global textile industry is one of the largest contributors to environmental pollution, primarily due to the widespread use of toxic, non-biodegradable, and carcinogenic synthetic dyes (Srivastava & Singh, 2019; Rubio et al., 2025). The processing of textiles demands massive water resources—for instance, producing a single T-shirt requires approximately 250 gallons of water—and discharges hazardous chemicals and pollutants into waterways (Sayem et al., 2021). While natural dyes, such as turmeric, present a highly desirable, renewable, and eco-friendly alternative that can even offer functional benefits

like UV protection, less allergic and antimicrobial properties (Sayem et al., 2021), however commercial adoption of natural dye is hindered by major limitations in conventional extraction and dyeing processes.

Traditional heat-based extraction methods, such as prolonged aqueous boiling, are often inefficient, consume significant time and energy, and yield inconsistent dye quality. Crucially, the excessive heat used in traditional boiling degrades thermolabile bio-active pigments, resulting in duller color shades and diminished color yields (Kalyani and Rafeekher, 2025; Yadav et al., 2025). To address these historical bottlenecks, recent advancements have shifted toward modern, non-conventional extraction techniques such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), which enhance extraction efficiency, preserve heat-sensitive compounds, and significantly reduce environmental impacts (Kalyani and Rafeekher, 2025; Yadav et al., 2025). Aligning with these modern advancements, this project aims to develop and investigate a high-efficiency, sustainable system for natural dye extraction and textile dyeing. The study systematically evaluates the effects of different extraction techniques on color intensity, particle size, and overall dyeing quality on cotton satin sheets. By integrating a combination of physical treatments—specifically freeze-drying (lyophilization) to protect pigments from thermal degradation, high-shear homogenization to reduce particle size, and sonication to induce acoustic cavitation for deeper dye penetration into fiber pores—this study demonstrates how upgraded natural dye processes can overcome traditional limitations and drive the textile industry toward sustainable, eco-friendly coloration.

2. METHODOLOGY

This study compared conventional extraction against the proposed advanced extraction technique using turmeric as a natural dye source. The turmeric used in this study was purchased from a local market. Approximately 19 g of turmeric was weighed and washed thoroughly to remove impurities, followed by the extraction techniques shown in Table 1. Deionised water (Millipore, France, 18.2 MΩ) was used throughout the study.

Table 1. Different techniques used for extraction of natural dye from turmeric

Technique	Details
A	Turmeric was blended with 400 mL water, followed by boiling for 30 minutes.
B	Turmeric was blended with 400 mL of water and boiled for 30 minutes, followed by homogenization and sonication for 5 minutes.
C	Turmeric was stored in a freezer at -80°C for 24 hours, followed by lyophilization (freeze-drying) for 48 hours. The sample was then blended and sieved prior to boiling for 30 minutes.
D (Proposed technique)	Turmeric was stored at -80°C for 24 hours and freeze-dried for 48 hours. Subsequently, the sample was blended, sieved, and boiled for 30 minutes, followed by homogenization and sonication for 5 minutes.

After extraction, the solution was subjected to analysis using UV-Vis spectrophotometry (3600i Plus, Shimadzu, Japan) to determine the colour absorbance and dynamic light

scattering (DLS) (Lifesizer 500, Anton Paar, Austria) for particle size analysis. Finally, cotton satin sheets (4 x 4 cm) were soaked in the extracted turmeric solution for 15 minutes for the dyeing process. A visual assessment survey was conducted with 10 respondents to evaluate user preferences regarding dyeing quality. Additionally, commercial turmeric powder was used as a control to compare its particle size and dyeing quality against the other techniques. The preparation of the dye solution from commercial turmeric powder followed the traditional extraction technique.

3. RESULTS AND DISCUSSION

3.1 Particle Size

The extraction techniques drastically influenced the particle size of the natural dyes. Dynamic Light Scattering (DLS) analysis demonstrated that turmeric extracted from technique D (proposed technique) successfully reduced the mean particle size to 1252.3 nm. This is significantly smaller compared to the turmeric from other techniques (Table 2). Most notably, the traditional technique (A) recorded a mean size of 4853.75 nm, and standard commercial turmeric powder measured 14,206.29 nm. The reduction to nano- and micro-sizes via homogenization ensures highly uniform dispersion in the solvent. As shown in Table 2, the standard deviation of the particle size quite high. This may be due to the agglomeration from the particle size.

Table 2. Particle size of turmeric from different extraction techniques using DLS analysis

Technique	Average Hydrodynamic diameter (nm)	Standard deviation (nm)
A	4853.75	545.62
B	1802.84	1002.65
C	1388.86	333.94
D (proposed technique)	1252.29	395.03
Commercial turmeric powder	14206.29	3788.46

3.2 Colour Intensity

UV-Vis spectrophotometry was utilized to evaluate the colour intensity of the bio-active yellow pigment extracted from the turmeric. Based on Figure 1, the proposed technique (D) achieved the highest absorbance peak, recording approximately 2.5 at a 425 nm wavelength. In contrast, the traditional extraction method (A) was left far behind, recording an absorbance of only around 1.2. This proves that the proposed technique successfully avoids pigment degradation and maximizes colour yield.

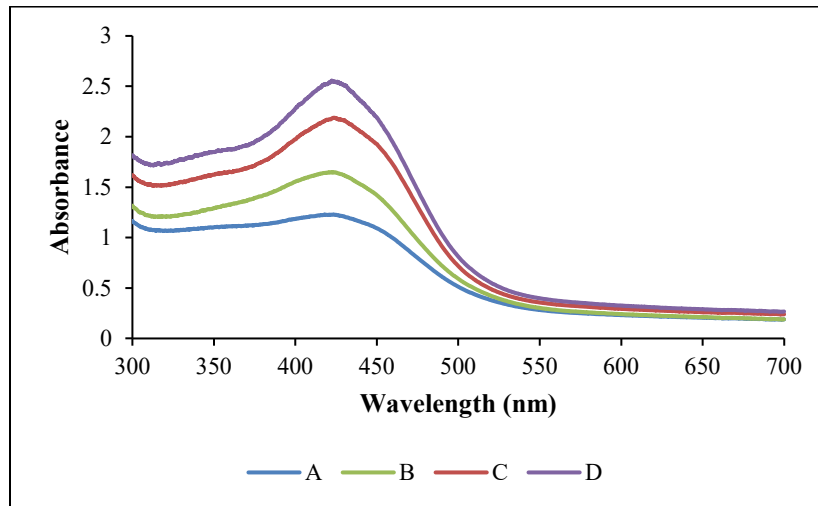


Figure 1. Colour intensity of turmeric extracted from different techniques.

3.3 Dyeing Quality on Fabric

Figure 2 shows the cotton satin sheets dyed with turmeric from different extraction techniques. A visual assessment survey involving 10 respondents yielded a 100% preference (10 out of 10) for the cotton satin sheets dyed using the technique D. The respondents conclusively determined that the proposed technique provides the best overall brightness and evenness compared to traditional method. Traditional extraction method produces large, inconsistent dye particles that exhibit poor affinity for textile fibres, leading to poor dispersion and uneven coloration. In contrast, the efficacy of the proposed technique lies in the combination of three mechanisms. Freeze-drying (lyophilization) is utilized to preserve the heat-sensitive chemical structure of turmeric from thermal degradation (Silva-Espinoza et al, 2019), creating a highly porous powder that increases surface area and enhances solubility. High-shear homogenization breaks down the dye particles into micro- or nano-sizes (Cano-Sarmiento et al., 2015). These smaller particles improve dye adherence to fabrics, thereby ensuring uniform dispersion (Yadav et al., 2025). Finally, sonication-assisted creates acoustic cavitation, which causes tiny bubbles to form and collapse, enhancing dye diffusion deep into fibre pores without the need for excessive heat or harsh chemical mordants (Repon et al., 2024; Kalyani & Rafeekher, 2025).

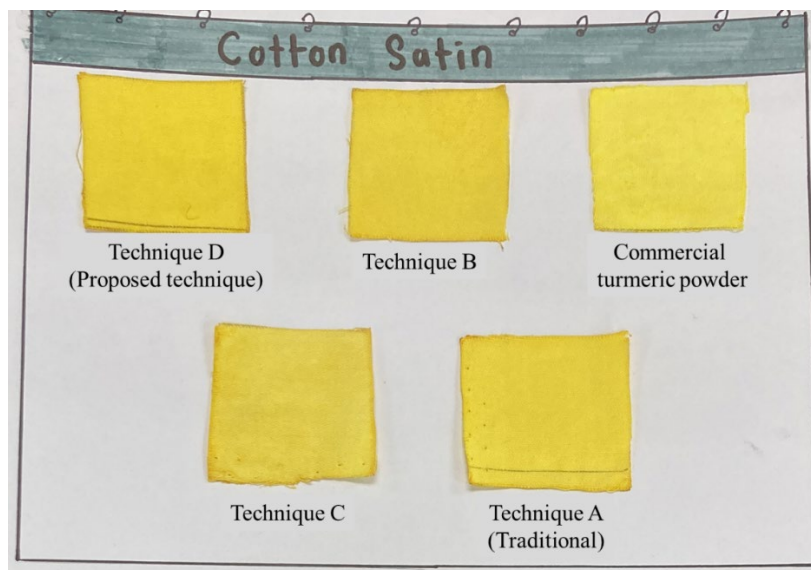


Figure 2. Cotton satin sheets dyed with turmeric from different extraction techniques.

4. CONCLUSION

Preliminary evidence successfully demonstrates that the combination of freeze-drying, homogenization, and sonication (proposed technique) is the most effective method for natural dye extraction and textile coloration. It resolves the historical bottlenecks of natural dyes by significantly improving colour intensity, particle uniformity, and dyeing quality. Furthermore, this project heavily aligns with Sustainable Development Goals (SDG) by offering a greener pathway for the textile industry. It promotes an eco-friendly sourcing cycle with a lower carbon footprint, speeds up dye penetration to maximize energy efficiency, and eliminates the need for toxic heavy-metal mordants. As a result, the textiles produced are hypoallergenic and safe, offering high potential for sustainable commercialization globally. To ensure the long-term success and scalability of the proposed technique, future research should prioritize standardized wash and light fastness testing to validate industrial durability, alongside expanding the protocol to other natural dye. From a commercial perspective, this innovation offers a high-value-added opportunity by transforming low-cost raw materials into premium, nano-scale dye powders which projected to provide high return of investment (ROI).

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