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Study on the dyeing effectiveness and the antibacterial ability of cotton fabric 100% using the extract from Muntingia Calabura leaves

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Abstract

In the context of the textile industry, which is the second largest polluter in the world just after the oil industry, the demand for natural components is increasing. And the environmental damage is increasing as the industry grows. This study focuses on *Muntingia calabura* leaves with the aim of exploring natural colorants capable of dyeing cotton fabric as a substitute for chemical dyes and developing an antibacterial finishing method for cotton fabric. The study employs color extraction methods using Ethanol 60% solvent and Deep Eutectic Solvents (DES), and dyeing is performed using microwave irradiation. Color measurement is conducted using an X-Rite Color i5 spectrophotometer, and color parameters are analyzed in the CIELab. Furthermore, the presence of antibacterial substances on the treated fabric is determined by FTIR spectroscopy, and the antibacterial efficacy of the treated cotton fabric is evaluated against two bacterial strains: gram-negative E. coli and gram-positive S. aureus. The Muntingia calabura leaves' extract demonstrated the ability to dye cotton fabric with Delta E of 36,53 (Ethanol 60%), 39,95 (DES) and the K/S color strength of 5,613 (Ethanol 60%), 6,576 (DES), along with impressive antibacterial activity, achieving up to 100% against E. coli and 96,5% against S. aureus. The dyed fabric exhibited high rubbing fastness at level 5 for both solvents in dry rubbing fastness and exhibited quite good color staining fastness to washing, reaching level 4-5.

Keywords: Muntingia calabura L. extract, Dyeing, antibacterial, cotton fabric, color strength, color difference.

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1. Introduction

The global textile and garment industry is currently facing significant environmental challenges, particularly in both developed and developing countries [1],[2]. The manufacturing process from raw materials to finished products consumes substantial amounts of water, energy, and chemicals, resulting in significant environmental impacts. In Vietnam, the textile and garment sector has achieved remarkable growth, becoming one of the key export industries and generating substantial employment opportunities [3], [4], [5]. As hygiene and health concerns continue to rise, antimicrobial fabrics, particularly those that are environmentally friendly, have become an inevitable trend [6], [7]. These fabrics not only help limit the spread of bacteria in healthcare settings but also play an important role in improving the quality and safety of daily-use textile products. The dyeing industry is characterized by high consumption of water and the extensive use of various chemicals in pre-treatment, dyeing, and finishing processes, all of which have a direct impact on the environment [8], [9]. Consequently, consumer demand for eco-friendly coloring agents is increasing. Natural dyes, being biodegradable and less toxic to humans and the

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environment, are considered a promising alternative for the sustainable fashion industry [10]. Cotton fabric, widely used for its softness, versatility, absorbency, and breathability, is also highly susceptible to microbial growth, including mold, fungi, and bacteria [11],[12]. Such microbial contamination can lead to unpleasant odors, mold formation, and even health risks for users, ultimately affecting the durability and overall quality of the product [13],[14]. Muntingia calabura leaves possess several medicinal benefits, such as cardioprotective, analgesic, antipyretic, and anti-inflammatory properties [15],[16]. These leaves contain various bioactive compounds, including flavonoids, tannins, and saponins, which have demonstrated strong antibacterial activity against different pathogenic microorganisms (Staphylococcus aureus, Bacillus cereus, Pseudomonas aeruginosa, and Escherichia coli) using the disc diffusion method [17],[18],[19],[20]. In 2020, Malaysian researchers successfully synthesized silver nanoparticles using Muntingia calabura leaf extracts and observed their strong antibacterial activity and potential for medical applications [21],[22]. More recent studies, including those conducted in Indonesia (2022) and by MosaChristas et al. (2022) have further highlighted the significant antioxidant and antibacterial properties of Muntingia calabura leaves, suggesting their potential in developing novel natural antimicrobial agents and quorum-sensing inhibitors [23],[24]. However, despite these promising findings, limited research has focused on the antibacterial potential of *Muntingia calabura* leaf extracts when applied to textile materials [25].
Given the growing environmental challenges, this study aims to explore sustainable alternatives to synthetic dyes by utilizing natural resources. Specifically, it investigates the dyeing performance and antimicrobial finishing potential of Muntingia calabura leaves' extract on 100% cotton fabric, develops a microwave-assisted extraction and dyeing approach using *Muntingia calabura* leaves as a natural colourant. Unlike previous studies that mainly focused on conventional extraction methods or colour properties alone, this work systematically investigates the combined effects of microwave processing on colour strength, colour difference, and functional performance, including antibacterial activity and colour fastness. Furthermore, the study provides a more comprehensive evaluation by correlating colourimetric results with surface morphology and chemical characteristics, thereby offering new insights into the potential of *Muntingia calabura* leaves for multifunctional and more sustainable textile dyeing applications.
This research will support to contribute to reducing environmental pollution and protecting human health within the textile dyeing and finishing industry [26-33].

2. Materials and methods

2.1 Materials

Muntingia calabura leaves was harvested in Dak Lak province, Viet Nam.
Untreated cotton fabric (raw fabric) is 100% knitted (Jersey Knit). Fabric weight is 180 g/m^2 with fabric width of 140cm at Shahi Exports PVT LTD (India).
Chemicals: Distilled water, Ethanol 99,5%, Axit Citric 98%, Chlorine Chloride 98%, Tannic Acid 0,1%, NaOH 98%, CH_3COOH purchased from a company of China.

2.2 Methods

When harvested, the leaves of the Muntingia calabura are preliminarily treated to remove the damaged leaves and wash them. Drying in the shade preserves higher flavonoid content. Continue drying the muntingia calabura leaves using an infrared dryer at a temperature below 60^{0}C until all moisture is removed. Finally, the muntingia calabura leaves were ground or milled into a fine powder (Figure 1).

Figure 1: Preparation of M. calabura extracts: (a) fresh Muntingia calabura leaves, (b) wash the Muntingia calabura leaves, (c) Muntingia calabura leaves powder

To synthesize the DES solvent, choline chloride and citric acid were selected with a mixing ratio of choline chloride: citric acid: water = 1: 2 : 25% [23]. Their ability to form a strong hydrogen bond network and increase viscosity gives DES solvents a unique structure, creating 'voids' of suitable size to accommodate and dissolve solute molecules, thereby enhancing flavonoid extraction efficiency. The addition of water also strengthens hydrogen bonding, and DES molecules can still retain water up to a certain amount. Furthermore, DES are biodegradable, nontoxic, nonvolatile, and nonflammable [8] [20].

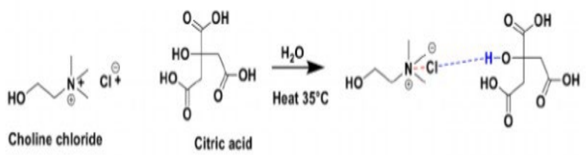


Figure 2: Hydrogen boding between the anion of choline chloride and the hydroxyl group of citric acid [9]

Muntingia calabura leaves' powder of 6 g with 100 ml of Ethanol 60% and DES 1:2 (Choline chloride: Acid citric) solution is ensured that Muntingia calabura leaves powder is evenly dispersed in the solution with an extraction ratio of 1:15 (Figure 3). Then it was microwaved at 560W for a duration of 5 minutes to extract dyeing solution.

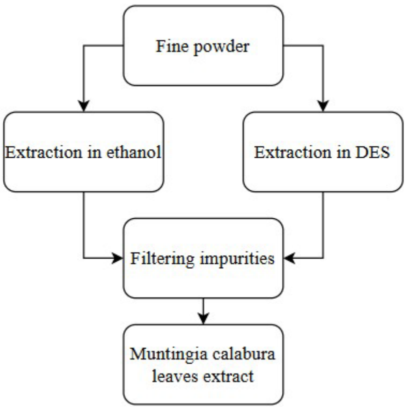


Figure 3. Diagram of the process of extracting pigments from Muntingia calabura L. leaves

Cotton fabric 100% is dyed with Muntingia calabura leaves extract with two solvents Ethanol 60%(E) and DES 1:2 (D) as below to order:

Survey 1: Investigate the impact of pH on color strength with changes in pH (pH ≈ 5, pH ≈ 6, pH ≈ 7).

Survey 2: Investigate the impact of dyeing time (3 min, 5 min and 7 min).

Survey 3: Investigation of antibacterial efficacy of samples

Before dyeing cotton fabric 100%, it needs to be mordanted with Tannic acid 8%, 90^{0}C for 1 hour. Then dyeing was carried out using a Ethanol 60% solvent and a 1:2 DES (Deep Eutectic Solvent) under dyeing conditions: (1) dyeing ratio 1:15, (2) extraction capacity 560W .Finally, colorimetric measurements were performed to compare the influence of the two solvents on color strength.

The equipment in the study including a heating magnetic stirrer (Velp, Italy), electronic scale (Ohaus PX224E, USA), microwave, dryer (Gavazzi),pH differential method (S220, Metter Toledo), scanning electron microscopy (SEM, TM4000Plus, Hitachi), Fourier-transform infrared spectrometer (FTIR, Brucker Tensor 37) and spectrophotometer machine (X-rite Color i5D, USA) were used to clarify contents of colorants as well as dyeability of dyed cotton fabrics. Color fastness of dyed fabrics to washing and rubbing was investigated according to the international standard method (ISO 105 – C06 A1S and ISO 105-X12). Antibacterial ability was assessed according to ASTM E2149.

Color Measurements
The following color system is used to assess the color: CIE L*a*b*. Results were examined using a spectrophotometer (Xrite Color i5, USA).

L*: Lightness of color
a*: Color coordinate on red (a*) - green (-a*) axis
b*: Color coordinates on the yellow (b*) - blue (-b*) axis

The color difference ΔE * is calculated using the formula:

$$\Delta E^* = \sqrt{\left(L_2^* - L_1^*\right)^2 + \left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2} \quad (1)$$

The level of coloration of the colored cotton fabric samples was determined by using the K/S value is the Kubelka-Munk formula:

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (2)$$

Where R is the reflection value, K and S are the absorption and the back scattering values, respectively.

3. Results and discussion

3.1. Evaluation of the Influence of pH on Color strength and Color Difference

The effect of pH on the dyeing performance of 100% cotton fabric was evaluated based on color strength (K/S) and color difference (ΔE) values. The results revealed that pH strongly influenced the color absorption ability and visual shade depth. As the pH increased from 5 to 6, both K/S and ΔE values rose markedly, reaching their maximum at pH 6 (K/S = 6.14 for extracted dye and 6.91 for dyed sample), indicating enhanced dye uptake and more vivid coloration. When the pH increased further to 7, both K/S and ΔE decreased significantly, suggesting reduced dye fixation and lighter shade formation. This behavior can be attributed to the chemical nature of cotton cellulose and dye molecules. At slightly acidic to near-neutral conditions (around pH 6), the cotton fiber surface is moderately protonated, allowing effective electrostatic attraction and hydrogen bonding between the hydroxyl groups of cellulose and the dye anions. These conditions favor dye penetration and stable fixation.
In contrast, at higher pH levels, excessive hydroxide ions promote partial hydrolysis of the dye molecules and reduce the availability of active sites on the fiber surface, resulting in lower color strength. Therefore, both K/S and ΔE analyses confirm that the optimal dyeing pH for 100% cotton is approximately 6, providing the best balance for dye-fiber interaction, leading to superior color absorption and visual intensity.

Table 1. Influence of pH on color parameters

Value	ΔE_{tb}	K/S_{tb}	Color of samples
Raw fabric	-	2.12	
pH ≈ 5 (E)	33.54	4.36	
pH ≈ 6 (E)	36.70	6.14	
pH ≈ 7 (E)	30.95	4.19	
pH ≈ 5 (D)	38.94	5.27	
pH ≈ 6 (D)	39.71	6.91	
pH ≈ 7 (D)	39.22	5.24	

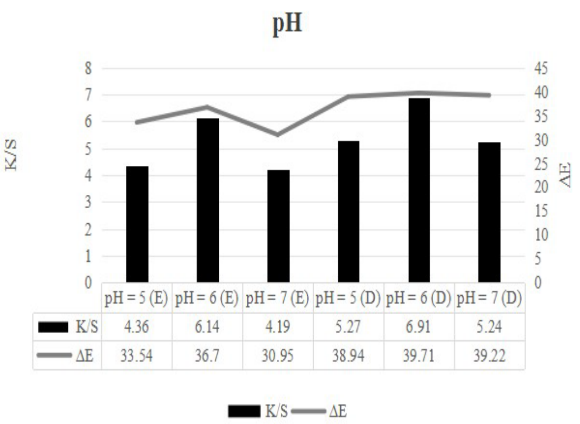


Figure 4. Impact of pH on color

3.2. Evaluation of the Influence of dyeing time on Color strength and Color Difference

Dyeing time significantly influences the color strength (K/S) and color difference (ΔE) of 100% cotton fabric. As the dyeing time increased from 3 to 5 minutes, both K/S and ΔE values rose noticeably, indicating improved dye penetration and fixation within the cotton structure. Cotton fibers contain numerous hydroxyl (–OH) groups in their cellulose chains, which can form hydrogen bonds with dye molecules. During the optimal dyeing time, these sites are effectively occupied, leading to maximum color absorption and a deeper shade.

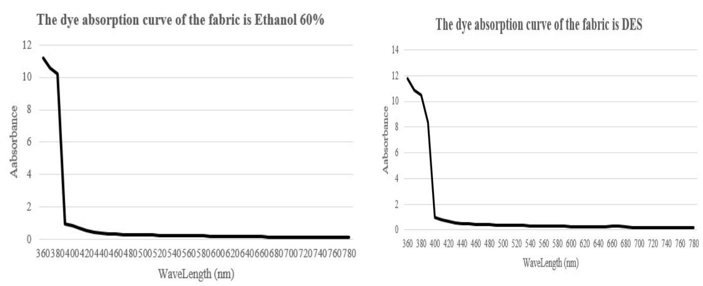
However, when dyeing continued to 7 minutes, both K/S and ΔE values decreased slightly. This reduction suggests that the fiber had reached saturation, and prolonged exposure caused partial desorption or dye hydrolysis, reducing dye–fiber bonding efficiency.

Overall, the results confirm that the suitable dyeing time for 100% cotton is around 5 minutes, when dye molecules fully interact with cellulose hydroxyl groups, resulting in the highest color intensity and visual color difference.

Table 2. Influence of on color parameters

Value	ΔE_{tb}	K/S_{tb}
Raw fabric	-	2.12
3 min (E)	23.76	4.36
5 min (E)	27.15	5.96
7 min (E)	36.59	5.29
3 min (D)	38.81	5.26
5 min (D)	38.80	6.99
7 min (D)	39.70	5.76

The dye absorption curve of the fabric in DES shows a higher absorbance intensity (around 350–430 nm) compared to the fabric dyed in ethanol, where the absorbance peak is usually lower and broader. This indicates that DES enhances dye solubility and interaction with the cotton fibers, leading to greater dye uptake.In contrast, The dye absorption curve of the fabric in ethanol shows less polar and having weaker hydrogen bonding capability results in lower dye absorption and poorer dye–fiber affinity. Consequently, fabrics dyed in ethanol typically exhibit lower color strength.
Overall, the DES system provides a more efficient dyeing environmentfor cotton by promoting stronger dye–fiber interactions and more uniform color distribution, leading to higher absorbance, deeper shade, and improved color consistency compared to ethanol.



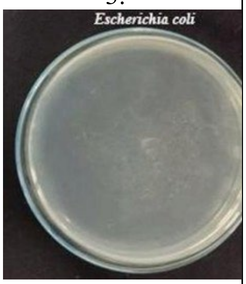
(a) (b)

Figure 5. *The dye absorption curve of the fabric is the best in survey 2: (a) Ethanol 60%, (b) DES*

The absorption curves of the two solvents Ethanol 60% and DES, although differing in value, show no significant difference and both peak at a wavelength of 360 nm. Therefore, fabrics dyed with the Muntingia calabura leaves' extract will exhibit the same color, which is the characteristic natural yellow color of Luteolin [10] [30] (Figure 5).

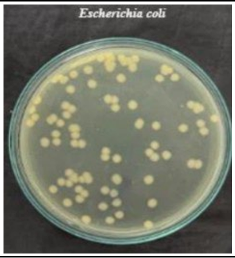
3.3. Evaluation efficiency of antibacterial ability

Table 3.The antibacterial efficacy of cotton fabric before washing

Fabric sample	E. coli	S. aureus
Untreated fabric	1. 	2. 
Treated sample	3. 	4. 

The antibacterial efficacy of cotton fabric treated with Muntingia calabura leaves extract against E. coli and S. aureus demonstrated significant results, with 100% inhibition against E. coli and 96.50% against S. aureus (Table 3). This highlights the natural antibacterial properties of the extract. Notably, the absence of mordant in this process presents a promising opportunity for the application of Muntingia calabura leaves extract in producing natural, safe, and environmentally friendly antibacterial textiles.

Table 4.The antibacterial efficacy of cotton fabric after 5 washes

Fabric sample	E.coli	S. aureus
Untreated fabric		
Treated sample		

The results of the antibacterial testing of cotton fabric treated with the extract of Muntingia calabura leaves after 5 washes show impressive efficacy in inhibiting the growth of E. coli (93.82%) and S. aureus (92.08%) (Table 4). A major challenge for natural antibacterial agents is maintaining their antibacterial activity after multiple washes, as they often significantly decrease. However, these results demonstrate the sustainability of the antibacterial activity of the Muntingia calabura leaves extract (flavonoids, triterpenoids, tannins) on cotton fabric which has been studied and surveyed in previous research. The washing process not only fails to reduce the antibacterial capability of the fabric but also helps remove some unnecessary impurities. This challenge has been widely reported in previous studies on plant-based antibacterial finishes.

3.4. Evaluation of fabric surface after treatment using SEM

The surface morphology of cotton fabrics before and after treatment with *Muntingia calabura* leaf extract was examined by SEM at magnifications of ×250 and ×1000, as shown in Figure 6. The untreated cotton fabric (Figure 6a) exhibits the typical flat, ribbon-like fibers with a twisted morphology and a relatively rough surface, indicating the presence of incompletely processed fibers. After treatment with *Muntingia calabura* leaf extract (Figure 6b), the cotton fibers show a noticeably smoother surface and improved uniformity among adjacent fibers. This morphological change suggests the deposition of extract components onto the fiber surface, which may contribute to the observed antibacterial performance of the treated fabric.

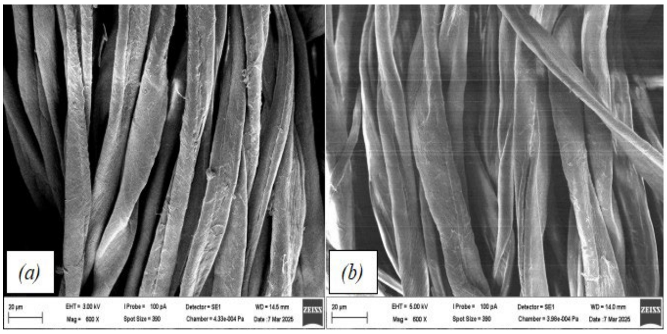


Figure 6. (a) SEM image of untreated cotton fabric, (b) SEM images of cotton fabric treated with Muntingia calabura leaves extract

3.5 FTIR Infrared Spectroscopy Results

The FTIR spectra of untreated and Muntingia calabura leaf extract–treated cotton fabrics exhibit similar characteristic absorption bands, indicating that the fundamental cellulose structure remains intact after treatment (Figure 7). The main cellulose-related peaks, including those associated with O–H and C–O vibrations, are clearly observed in both spectra, confirming that no chemical degradation of the cellulose backbone occurred during the treatment process.In the treated cotton fabric, an absorption band observed at 1001.47 cm^{-1} is attributed to C–O stretching vibrations of cellulose and may also be associated with contributions from tannins or flavonoid compounds present in the Muntingia calabura leaf extract, particularly C–OH groups linked to aromatic rings. Compared with the untreated fabric, slight shifts and increased intensities are observed in the bands around 3300 cm^{-1}, corresponding to O–H stretching vibrations, and around 1630 cm^{-1}, which are related to O–H bending of absorbed water or phenolic groups.

These spectral changes suggest the formation of hydrogen-bonding interactions between phenolic compounds from the extract and the hydroxyl groups of cellulose. Combined with the SEM observations, the FTIR results support the successful adsorption of bioactive compounds from the Muntingia calabura leaf extract onto the cotton fiber surface, without altering the inherent chemical structure of cellulose.

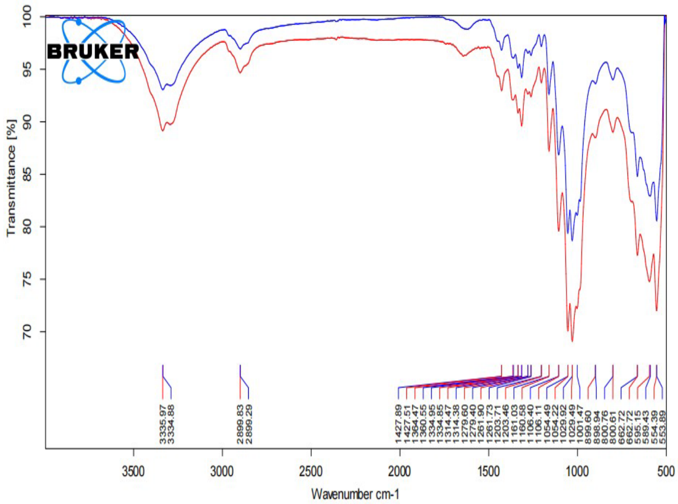


Figure 7 The FTIR spectra of untreated cotton fabric (red) and cotton fabric treated with the extract of Muntingia calabura leaves (green)

3.6 Results fastness of fabric

The color fastness to washing with ECE soap of the fabric dyed using the 60% ethanol solvent reached grade 3, while the DES solvent achieved grades 2–3. The slightly lower fastness of the DES-dyed fabric may be attributed to the natural origin of the dye, which generally exhibits lower affinity to cotton compared with synthetic dyes. Furthermore, possible interactions between DES components and the surfactants in ECE soap could alter dye solubility and weaken dye–fiber bonding, thereby reducing wash fastness. Despite this, the color staining on adjacent fabrics was good, rated at grades 4–5 and 5. For chemical washing (C_2Cl_4), the color fastness of fabrics dyed with the ethanol solvent achieved grades 3–4, while those dyed with the DES solvent reached grade 3.

The color staining performance remained satisfactory, with ratings of ratings of 4–5 and 5, respectively. In the rubbing fastness test, fabrics dyed with 60% ethanol showed high ratings (dry: 5; wet: 4–5), while those dyed with DES solvent exhibited slightly lower yet comparable values (dry: 5; wet: 4). In both cases, the wet rubbing fastness was lower than the dry rubbing fastness, likely due to moisture reducing the interaction strength between dye molecules and cellulose, thus making the color more susceptible to abrasion and fading under humid conditions.

4. Conclusion

Through the study of microwave-assisted dyeing of cotton fabric with Muntingia calabura leaf extract using 60% ethanol and DES solvents, antibacterial finishing without mordant was successfully achieved. The optimal dyeing conditions and antibacterial finishing for 100% cotton fabric were determined as follows: extraction ratio 1:15, pH 6, liquor ratio 1:15, drying temperature 60°C (560W), dyeing time 5 minutes, and 8% tannic acid mordant.

The dyed cotton fabrics exhibited good rubbing and washing fastness, confirming the effective bonding between dye molecules and the cellulose structure of cotton. Microwave-assisted dyeing technology demonstrates potential for energy-efficient, eco-friendly natural dyeing, while the antibacterial functionality achieved without chemical mordants further contributes to sustainable textile processing. This study was conducted under laboratory-scale conditions, and the obtained results may not fully reflect the performance under industrial environments. Future research will focus on process scale-up, application to other fibre types, and evaluation of the durability and functional performance of the treated fabrics under practical use conditions.

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