

Araştırma Makalesi / Research Article

SUSTAINABLE DYEING OF POLYESTER FABRICS USING NATURAL SOURCE (COCOS NUCIFERA PEEL) EXTRACT: EVALUATION OF COLORATION AND FASTNESS

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ABSTRACT: Coconut peel-extracted dyes were used to dye polyester fabric at concentrations of 2%, 3%, and 4%, with an alum mordant and vinegar, and without a mordant. The dyeing was performed at 135 °C and the characterization of extracted colorant, color-fastness properties—including color fastness to washing, light, and perspiration—were evaluated. Fourier Transform Infrared Spectroscopy (FT-IR) and Scanning Electron Microscopy (SEM) were used to analyze chemical interactions of the dyed samples and the surface morphology. The purpose of this study is to examine the durability and dyeing process of polyester fabrics dyed using a natural dye made from coconut peel. By evaluating coconut peel extract as a feasible natural dye source, the study promotes the development of environmentally acceptable, sustainable alternatives to synthetic dyes. The utilization of coconut peel, an underutilized agricultural waste, as a sustainable natural dye for polyester—a fabric that typically has a low affinity for natural dyes—is novel in this study. The work provides fresh insights into enhancing the performance of natural dyes on synthetic textiles by comparing vinegar and alum mordants and analyzing dye uptake at high temperatures. Coconut peel extract can serve as an efficient, environmentally acceptable dye source for sustainable polyester dyeing, as evidenced by FT-IR and SEM analyses of chemical interactions and surface morphology.

Keywords: Natural dye, Alum Mordant, Eco-Friendly Dyeing, Colorfastness, Coconut Peel, Alternative Dyes

POLYESTER KUMAŞLARIN DOĞAL KAYNAK (COCOS NUCIFERA KABUĞU) EKSTRAKTI KULLANILARAK SÜRDÜRÜLEBİLİR BOYANMASI: RENKLENDİRME VE HASLIK ÖZELLİKLERİNİN DEĞERLENDİRİLMESİ

ÖZ: Hindistan cevizi kabuğundan ekstrakte edilen boyarmaddeler, mordan olarak şap ve sirke kullanılarak ve mordan kullanılmadan, %2, %3 ve %4 konsantrasyonlarında poliester kumaşın boyanmasında kullanılmıştır. Boyama işlemi 135 °C'de gerçekleştirilmiş ve ekstrakte edilen renklendiricinin karakterizasyonu ile yıkamaya, ışığa ve tere karşı renk haslığı da dâhil olmak üzere renk haslığı özellikleri değerlendirilmiştir. Fourier Dönüşümlü Kızılötesi Spektroskopisi (FT-IR) ve Taramalı Elektron Mikroskobu (SEM) boyanmış numunelerin kimyasal etkileşimlerini ve yüzey morfolojisini analiz etmek için kullanılmıştır. Bu çalışmanın amacı, hindistan cevizi kabuğundan elde edilen doğal bir boyarmadde kullanılarak boyanan polyester kumaşların dayanıklılığını ve boyama sürecini incelemektir. Hindistan cevizi kabuğu ekstraktının uygulanabilir bir doğal boyarmadde kaynağı olarak değerlendirilmesiyle, çalışma sentetik boyarmaddelere çevresel açıdan kabul edilebilir ve sürdürülebilir alternatiflerin geliştirilmesini teşvik etmektedir. Yeterince değerlendirilmeyen bir tarımsal atık olan hindistan cevizi kabuğunun, genellikle doğal boyarmaddelere karşı düşük afiniteye sahip polyester için sürdürülebilir bir doğal boyarmadde olarak kullanılması, bu çalışmanın yenilikçi yönüdür. Çalışma, sirke ve şap mordanlarını karşılaştırarak ve yüksek sıcaklıklarda boyarmadde alımını analiz ederek, doğal boyarmaddelerin sentetik tekstiller üzerindeki performansını artırmaya yönelik yeni bilgiler sunmaktadır. Hindistan cevizi kabuğu ekstraktı, kimyasal etkileşimlerin ve yüzey morfolojisinin FT-IR ve SEM analizleriyle ortaya konduğu üzere, sürdürülebilir polyester boyamacılığı için etkili ve çevre dostu bir boya kaynağı olarak kullanılabilir.

Anahtar Kelimeler: Doğal boya, Alum Mordanı, Ekolojik Boyama, Renk Haslığı, Hindistan Cevizi Kabuğu, Alternatif Boyalar

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1. INTRODUCTION

The textile industry has been seeking ecologically friendly and sustainable substitutes for chemical dyes, which present potential risks to human health and the environment because of their hazardous chemical composition [1, 2]. The release of synthetic dyes into aquatic ecosystems without treatment results in water contamination, bioaccumulation, and enduring ecological damage, while also posing carcinogenic and mutagenic risks to human health, including problems with the skin, bone damage, renal complications, liver complications, kidney damage, infertility, cancer, and premature births [3-5]. In this situation, natural dyes made from renewable resources present a viable option [2, 6]. Among these, dyes derived from plant-based materials have attracted a lot of consideration due to their biodegradability and favorable effects on the environment [7-9].

Coconut peel, a natural source of color, that is usually discarded as agricultural waste, is one of the important byproducts produced by the multipurpose crop coconut (*Cocos nucifera*) [10, 11], which is widely farmed in tropical countries like Indonesia, Philippines, Thailand, India, Bangladesh, South Africa, and so on [12]. Coconut peel has been shown in earlier studies to contain tannins, flavonoids, and other pigment components, suggesting that it could be used as a natural source of color [13-15]. The use of coconut peel as a dye complements sustainable development and green chemistry concepts, while also encouraging waste valorization [16-18].

Polyester is a well-recognized synthetic fabric renowned for its strength and versatility [19, 20]. Despite this, due to containing several reactive groups and its hydrophobicity, polyester dyeing with natural dyes poses special difficulties [21, 22]. Consequently, it is essential to investigate and develop innovative dyeing methodologies such as the application of appropriate mordants, carrier- assisted dyeing, modifying the surface, or elevated temperature and pressure treatments to augment the affinity of natural dyes for polyester fibers. However, it is crucial to investigate and improve dyeing methods to increase the affinity of natural dyes for polyester fibers in order to address these problems [23-25].

In response to the rising demand for ecologically friendly and sustainable alternatives to hazardous synthetic dyes that pose risks to human health and the environment, Hossain et al. investigated the jute and silk fabrics dyeing with an extraction of coconut leaves in aqueous medium, evaluating color fastness, strength, and shade variations both with and without metal salt mordants, and found that color fastness was improved, particularly in silk [26]. Eren et al. reported that supercritical CO₂ polyester dyeing with natural madder provided an effective, eco-friendly, and sustainable alternative to typical high-temperature, high-chemical dyeing methods, producing fabrics with good color strength, satisfactory fastness, and preserved physical integrity without the need for auxiliary chemicals [20]. Adeel et al. examined the bio-mordants' usage to improve the color yield and fastness of the

dyed fabrics while dyeing wool sustainably using ultrasonic radiation and coconut coir extract [27]. A study reported the effects of using Lac and Catechu to dye poly-trimethylene terephthalate (PTT), poly-lactic acid (PLA), and poly-ethylene terephthalate (PET) fibers by Sen et al. It finds that PTT has a greater color absorption and that Catechu functions as a bio-mordant [28]. Bhuiyan et al. studied henna dyeing of polyester fibers without metallic mordants and found that higher temperatures increased dye absorption and yielded excellent color fastness, supporting eco-friendly dyeing approaches [29]. A study conducted by A. Utama et al. concluded that natural dyes from coconut fiber waste and avocado leaves provide unique brown and dark shades, which compete with the quality of other natural dyes, and their use in batik dyeing enhances economic value, supports a green economy, and offers micro, small, and medium enterprises a sustainable alternative to synthetic dyes [11]. Again, M. H. Rodiah and his team reported that natural dyes from *Cocos nucifera* mesocarp and exocarp, extracted via microwave-assisted 0.8 M NaOH for 4 minutes, effectively dyed cotton fabrics, with 7.5% tannic acid mordant significantly enhancing color depth and wash fastness, demonstrating its potential as an environmentally friendly alternative to synthetic dyes [2]. Similarly, Adeel et al. applied an extract of coconut coir for silk dyeing and described better efficiencies as well as fastness properties [17]. The researchers have studied the effects of different mordants on the dyeing of cotton fabric using coconut husk [30]. These studies have validated the dyeing effect of coconut-based products, yet most of them were carried out on cotton, silk, or wool, and not mainly on polyester fabric.

Since limited work has been done about dyeing of polyester fabrics using natural extract from coconut peel and evaluating its dyeing and color fastness properties, thus the purpose of this study is to assess the dyeing performance of coconut peel extract on polyester fabric, with particular attention to dye uptake, color fastness, and the effect of mordants. The specific objectives are to extract a natural dye from coconut peel, apply the dye to polyester fabric with and without mordants, compare alum and vinegar mordants, investigate color fastness under various conditions, and qualitatively observe surface/structural changes in dyed fabrics using SEM and FTIR analysis. Alum mordant and vinegar were selected as both are inexpensive, readily available materials that also have the ability to improve patch fixation to fibers and color fastness in natural dyeing systems. Moreover, this work is important because it helps value waste coconut peel, and also this substrate provides a simple, low-cost, and more sustainable dyeing method for polyester fabric, offering an environmentally friendly alternative to conventional synthetic dyes.

2. MATERIAL AND METHODS

2.1. Materials

In this study, coconut husks were collected from the local market in Dhaka, Bangladesh. Fabric samples of 1/1 plain weave 100% polyester fabric with 60/50 ends and picks per inch were acquired

from CODS Limited, Bangladesh. Additionally, alum (analytical grade) mordant and vinegar were purchased at the chemical market in Dhaka, Bangladesh.

2.1. Methods

2.2.1. Preparation of Raw Material

The natural source of the dye was coconut husks. The coconut husks collected were manually cleaned by the removal of visible impurities. Subsequently, these husks were cleaned repeatedly with distilled water to eliminate mud, dust, and foreign materials. Again, the coconut husks were washed and then dried for dye extraction.

2.2.2. Dye Extraction from Coconut Husks

The dye was obtained through the traditional method of aqueous extraction from dried coconut husk. This was done by taking 100 g of clean, dried coconut husk mixed with distilled water to create a material-to-liquor ratio (w/v) of 1:10. Coconut husk containing the coloring compounds was boiled at 100°C for a duration of 2 hours. After extraction, the solution was cooled and subsequently filtered through Whatman filter paper to remove solid residues and obtain a clear, colored extract. Lastly, the extracted color solution was evaporated at boiling temperature to produce the dye powder. The dyeing experiments were then performed using the powder form to maintain a standard concentration.

2.2.3. Dyeing and Mordanting of Polyester Fabric

The polyester fabric samples were dyed with a natural dye extracted from coconut husk using the exhaust dyeing method at

high temperature and pressure. There were three dyeing systems: natural dye with alum mordant, natural dye with vinegar and buffer, and only natural dye. Alum served as the conventional mordant when vinegar was used to acidify the pH instead of mediating mordancy on its own.

A polyester fabric (10 g) for each of the different experiments was dyed with 2%, 3%, and 4% concentrations of dye based on the weight of fabric. The liquor volume was the same across all reactions (100 mL), and a 1:10 material-to-liquor ratio was maintained. The pH of the dyebath was recorded prior to dyeing: with alum assistance, the pH was 3.8, while in the vinegar-assisted acidic bath, it was 3.5.

The dyeing process included an initial step of loading the water and fabric at 40 °C (Figure 1). The temperature was raised at about 2.5 °C/min to 50 °C, followed by the addition of leveling agent, buffer, dye extract, dispersing agent, and alum or vinegar, as known in the dyeing system. At approximately 60 °C, the pH of the solution was determined to ensure the conditions for acidic dyeing are appropriate. It was then heated to 135 °C at a rate of approximately 2.5°C/min and held for 60 min in order to aid dye diffusion into the polyester fiber.

In the dyeing process, the prepared dye-liquid was added to the dyed sample, and reduction clearing was performed at 98 °C for 20 min to remove unfixed dye from the fabric surface and enhance washing fastness. The bath was then cooled down to 55 °C utilizing a cooling coil, and the fabrics taken out were washed, dried, and prepped for color strength and fastness testing.

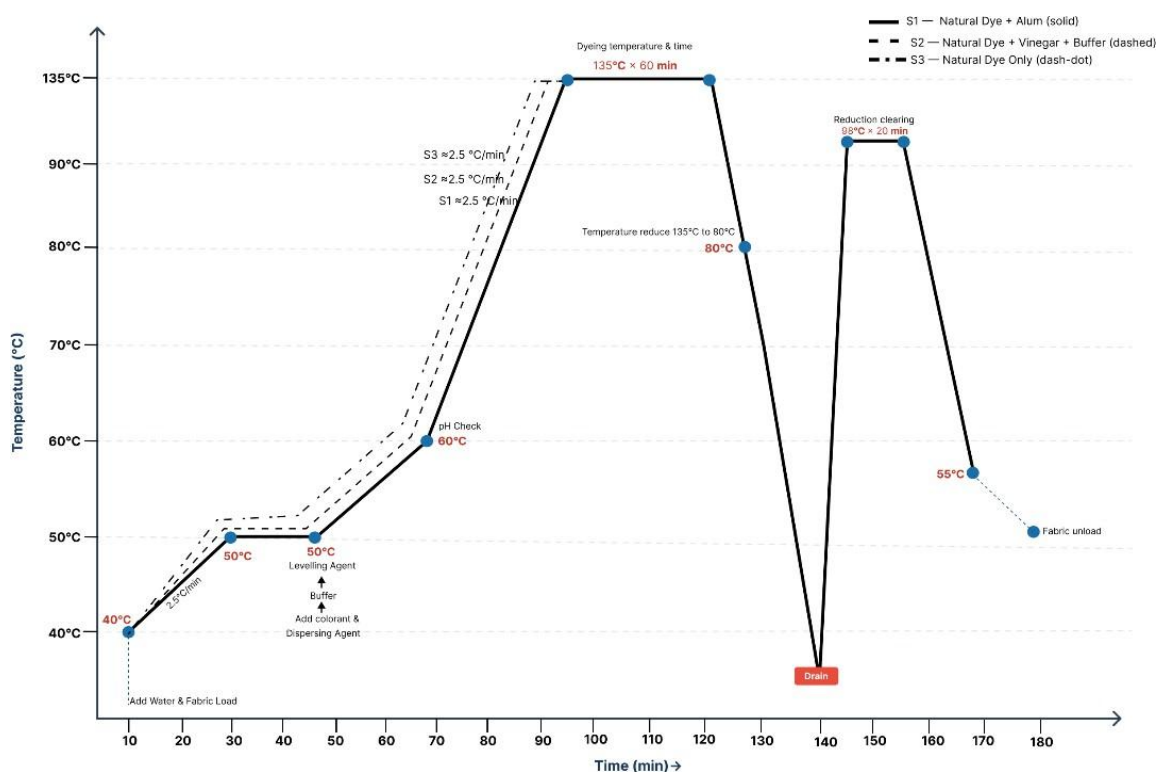


Figure 1. Dyeing curve of polyester fabric using coconut husk natural dye under alum-assisted, vinegar-assisted, and natural dye-only conditions

2.2.4. Characterizations

2.2.4.1. Analysis of Color

The color depth of the dyed fabrics was measured by following the K/S value. Similarly, the depth of the colored materials' shade was measured using the K/S values for the respective hues. The Kubelka-Munk equation is used by a color-measuring instrument (Datacolor 650, USA) to determine the samples' K/S values (Equation 1)

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

Where R represents the reflectance percentage, S is the dye scattering coefficient, and K is the dye absorption coefficient. The attenuation ratio of light due to scattering and absorption was used to compute this value, and it was found that reflectance affected this ratio. The results were found for each sample.

2.2.4.2. Fourier Transform Spectrophotometry

Fourier transform spectrophotometry was used to evaluate the chemical structure of polyester fabric and natural dye extract from coconut peel by IR Prestige-21 (Shimadzu Corporation, Japan) with MIRacle-10 Single Reflection ATR accessory. The spectra of the samples were recorded at a resolution of 4 cm^{-1} over the range $500\text{--}4000 \text{ cm}^{-1}$.

2.2.4.3 Scanning Electron Microscopy

Dyed polyester fabrics were examined using a SEM at 15 K magnification (SU 1510, Hitachi, Japan) to assess their morphological properties.

2.2.4.4 Color Fastness Tests

The following standards were used to evaluate the color fastness of fabrics dyed with coconut husk extract (Table 1).

Table 1. Color fastness test standards used for coconut peel extract-dyed polyester fabrics

Color Fastness Tests	ISO Standard
Color Fastness to Washing	ISO 105-C06
Color Fastness to Water	ISO 105-E01
Color Fastness to Perspiration (Acid and Alkaline)	ISO 105-E04
Color Fastness to Light	ISO 105-B02
Color Fastness to Rubbing	ISO 105-X12

3. RESULTS AND DISCUSSIONS

3.1. Dyed Sample

The polyester fabric samples dyed at a 3% shade using only alum mordant, vinegar, and water are shown in Figure 2.



Figure 2. Samples dyed at a 3% shade using a) alum mordant, b) vinegar, and c) water only

3.2. Color Strength Evaluation

3.2.1. K/S Values after Color Fastness to Washing

Alum-mordanted fabric focused at 3% shade had a higher K/S value (K/S value from 1.30 for the fabric dyed without mordant and 1.67 for the alum-treated fabric appreciated as well), showing better retention of color for washing fastness (Figure 3). Similarly, alum also increased the K/S value to 1.52 (compared with 1.40 for the non-mordanted sample) at 4% shade, but vinegar produced a slightly higher value of 1.64. It means: alum increases the affinity of remanent dye fixation during washing, particularly at medium shade intensities. Alum helps dye molecules to attach more strongly to the surface of textiles, making them coordinate complex bonds with the fabric, and loss during washing is considerably lower.

3.2.2. K/S Values after Color Fastness to Water

Alum mordants performed very well with respect to the fastness to water test at both 2% and 3% shade levels. The average K/S values of the alum-treated samples were 1.55 and 1.87, while for the non-mordanted ones, these values were equal to 1.49 and 1.48, respectively (Figure 4). Alum resulted in the highest K/S value of any treatment at 3% shade, indicating greater water extraction resistance. Vinegar gave the highest value at a concentration of 4%, giving a value of 1.82, while alum showed better results than the fabric dyed with non-mordant. Thus, alum is visibly efficient regarding water fastness, especially for low and middle shade depths.

3.2.3. K/S Values after Color Fastness to Acid Perspiration

The comparative effect of color retention showed that both alum and vinegar improved the color retention over non-mordanted

dyed fabric for acid perspiration (Figure 5). Alum at the 2 %, 3%, and 4 % shades showed K/S values of 1.50, 1.68, and 1.59, while the non-mordanted samples provided lower values of K/S for the same shades, such as 1.48, 1.55, and 1.22. This is evidence that the alum works to make the dye more resistant to acidic conditions from perspiration. In this regard, it is interesting to observe that vinegar produced higher K/S values than alum in this test, but only slightly so; for instance, at 4% shade, it has a K/S of 1.90.

So, it can be concluded that the semi-completion of acid perspiration fastness was improved by alum than no mordant, but better results were obtained with vinegar application under acidic conditions. Therefore, the results indicate that alum mordanting improved the acid perspiration fastness of the treated sample compared with the non-mordanted condition; however, vinegar application under acidic conditions exhibited the highest fastness performance, exhibiting a more pronounced beneficial effect.

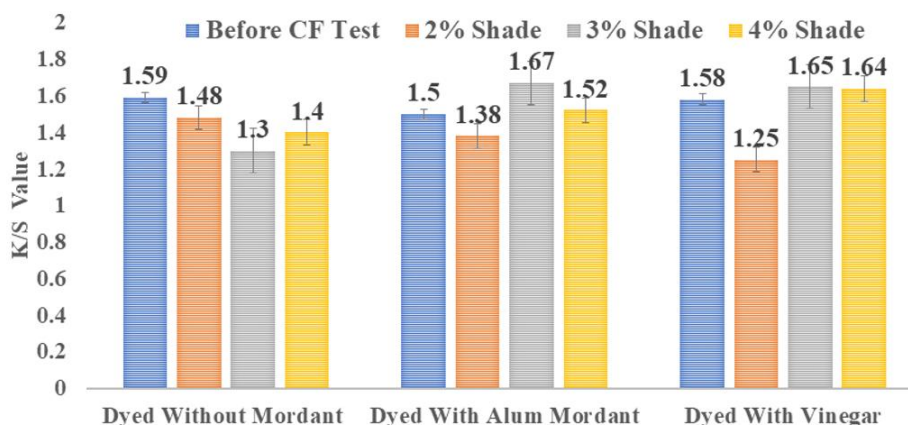


Figure 3. Comparison between the K/S values of dyed samples before and after color fastness to washing testing

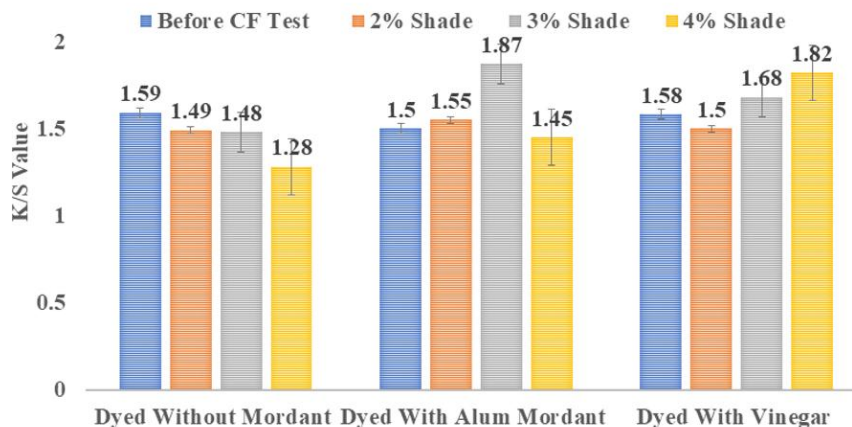


Figure 4. Comparison between the K/S values of dyed samples before and after the color fastness to water testing

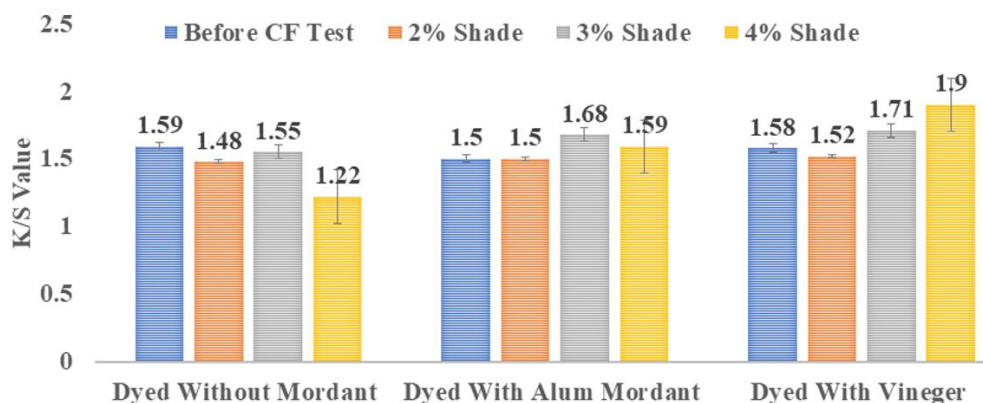


Figure 5. Comparison between the K/S values of dyed samples before and after color fastness to acid perspiration testing

3.2.4. K/S Values after Color Fastness to Alkaline Perspiration

In alkaline perspiration, very good results were obtained with alum mordant at shade levels of 2% and 3% (Figure 6). The K/S of the treated samples were 1.60 and 1.84 in alum; the non-mordanted samples were found to have K/S values: 1.40 and 1.53. In this way, the effects of lacquer on the stability of dye were studied under alkaline perspiration. Alum achieved a K/S value of 1.52 at 4% shade, which was higher than the non-mordanted sample but lower than that produced with vinegar. In each case, the 3% shade level exhibited the best and most consistent alkaline perspiration fastness, particularly for the alum-mordanted samples.

3.2.5. K/S Values after Color Fastness to Light

Overall, the light fastness (blue wool scale for light fastness) results indicated more color retention in alum-mordanted fabric compared to non-mordanted dyed fabric at all shade levels (Figure 7). The K/S values for the 2%, 3%, and 4% shades of alum-treated samples were found to be 1.25, 1.44, and 1.65, respectively, whereas the corresponding values of non-mordanted samples were lower. It significantly suggests that fading under light exposure benefited from alum. However, it can be inferred that vinegar gave the best K/S values among all different dyeing conditions in this test, especially at 4% shade, giving a K/S of 1.77. Consequently, alum had a positive effect on light fastness (compared to dyeing without mordant), whereas in this case, vinegar showed better resistance against to light fading.

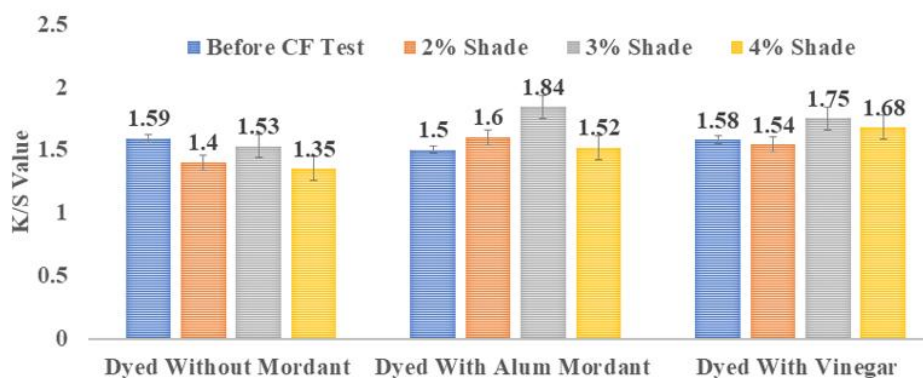


Figure 6. Comparison between the K/S values of dyed samples before and after color fastness to alkaline perspiration testing

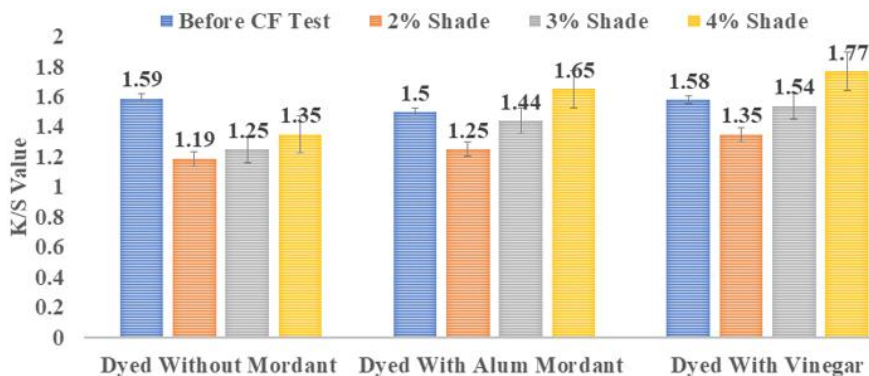


Figure 7. Comparison between the K/S values of dyed samples before and after color fastness to light testing

3.3. Structural Observations

The chemical interactions between polyester and coconut peel extract were examined using FT-IR analysis, which is shown in Figure 8. The coconut peel dye's potential as a natural dye was demonstrated by the distinctive peaks in its FTIR spectrum that corresponded to flavonoids, tannins, and polyphenolic chemicals [31]. After dyeing with alum mordant, changes in spectral bands were noted, indicating that the dye molecules and the fiber were interacting chemically. While peaks at 1700–1600 cm^{-1} ($\text{C}=\text{O}$

stretching) indicated good dye attachment [32], further absorption in the 3300–3400 cm^{-1} region suggested hydrogen bonding through $-\text{OH}$ groups like different polyphenolic groups [31]. A stable dye-mordant-fiber combination was confirmed by the alum-mordanted samples' increased absorption in the 1600–1500 cm^{-1} range [32]. These changes in spectra validate that the alum mordant increased the fixation of coconut peel dye onto polyester fabric. The FT-IR results confirm the surface deposition and better dye coverage of alum-mordanted dyed fabric, also observed by incorporating data from SEM results.

3.4. Morphological Analysis by SEM

The analysis using SEM for the alum-mordanted dyed fabric was performed, and a surface change after dyeing with coconut peel extract (Figure 9). It is observed less smoothly and depicts a roughish texture of fibers, demonstrating enhanced deposition and uniform adherence of dye particles onto the polyester fiber surface. The higher magnification images provide some insights into the more continuous and homogenous layer coating over the fiber

surface, likely due to the potential role of alum in promoting physical interaction between the dye and the fiber. Alum probably serves as a bridge between the dye molecules and the surface of the fabric itself, anchoring it more firmly. The small particles and uneven surfaces favor the formation of a layer of dye on the fiber surface. Based on these observations, it is inferred that the dye fixation of fabrics improved by using an alum mordant helps to obtain a more homogeneous coverage of dyed fibers [22].

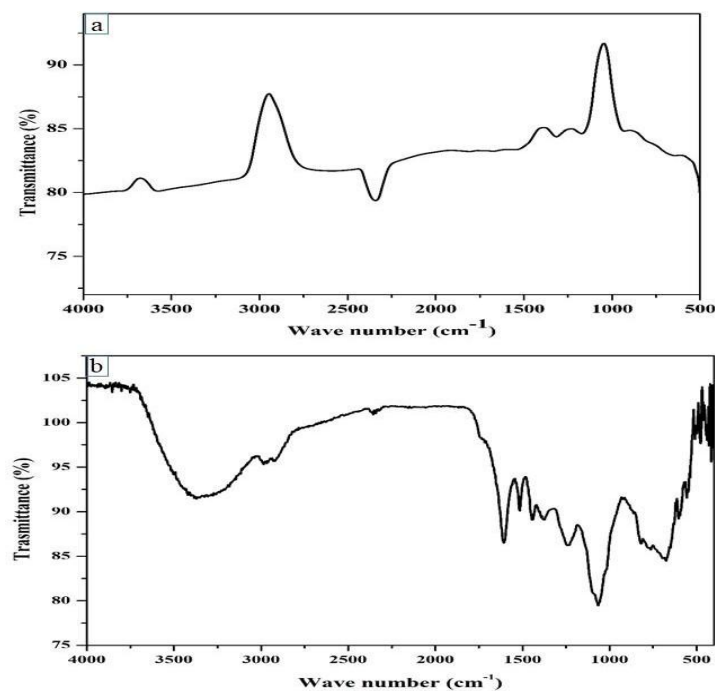


Figure 8. FT-IR analysis of a) dye extracted from coconut peel, b) dyed fabric

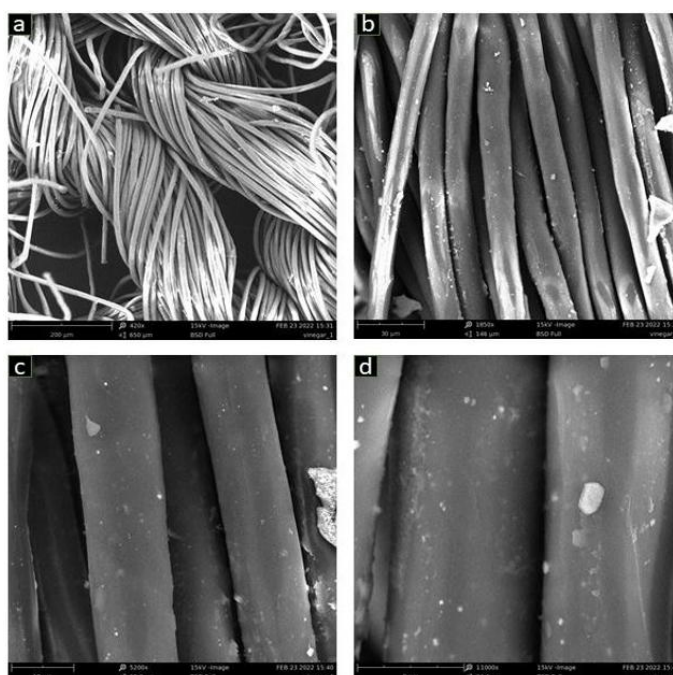


Figure 9. SEM images of the alum mordant-dyed fabric at different magnifications, with scale bars of a) 200 µm, b) 30 µm, c) 10 µm, and d) 5 µm

3.5. Color Fastness

Dyeing of polyester fabrics with coconut peel extract was performed at three conditions: (i) with alum mordant, (ii) dyeing with vinegar-assisted, and (iii) without mordant. Color fastness at 2%, 3%, and 4% shade concentration (% o.w.f.) was determined. Alum, as the mordant, improved all types of fastness properties compared to the vinegar and non-mordanted samples (Figure 10)

3.5.1. Effect of Alum Mordant on Color Fastness

The overall fastness performance was highest for alum-mordanted samples. Washing fastness increased from 4 (2%) to 4–5 (3–4%). Overall fastness to water was 4–5 on all shades. Fastness to acid and alkaline perspiration was 4–4, 4–5, meaning very good resistance to sweat conditions. The dry rubbing fastness increased from 3–5 to 4, and the wet rubbing fastness improved from 3 to 3–5. Light fastness varied between 2–3 (2%) and 3 (3–4%), meaning that the product has some resistance to light. These results suggest a strong dye-fiber interaction, which may be attributed to alum assistance in fixation [32]. By making it easier for a stable dye-mordant-fiber complex to form, alum mordant improves the dye's affinity for the fabric. However, a major negative side of plant-based dyes is their sensitivity to UV light, which is most likely the cause of the reduced light fastness.

3.5.2. Effect of Vinegar on Color Fastness

The samples treated with vinegar were moderately fast as well. The washing fastness showed a range from 3–5 to 4, and the water fastness remained constant at values of 4–4–5. Perspiration fastness properties to acid and alkaline ranged from 3–5 to 4. Dry rubbing fastness was improved from 3 to 3–4, and wet rubbing fastness was found in the range of 2–3 to 3–4. Its light fastness was also quite low, rated 2–2–3. In comparison with alum-mordanted samples, the vinegar-treated samples generally exhibited a slightly lower fastness performance, possibly due to weaker dye-fiber interactions under acidic treatment conditions.

3.5.3. Effect of Dyeing Without Mordant

Untreated samples received the worst fastness performance. Washing and water fastness varied from 2–3, while perspiration fastness was maintained within 2–3. Dry rubbing scored 2 to 3, while wet rubbing was lowest at two. Light fastness of 1–2 was exhibited at all concentrations. It supports a weak physical bonding of dye and fiber without help from mordants. In conclusion, alum outperformed all fastness tests across the board with washing, water, perspiration, and rubbing fastness tests, followed closely by vinegar and non-mordanted samples, which fared the worst. Increase in dye concentration (2–4% o.w.f.) only moderately increased color yield but did not markedly differ from the main trend.

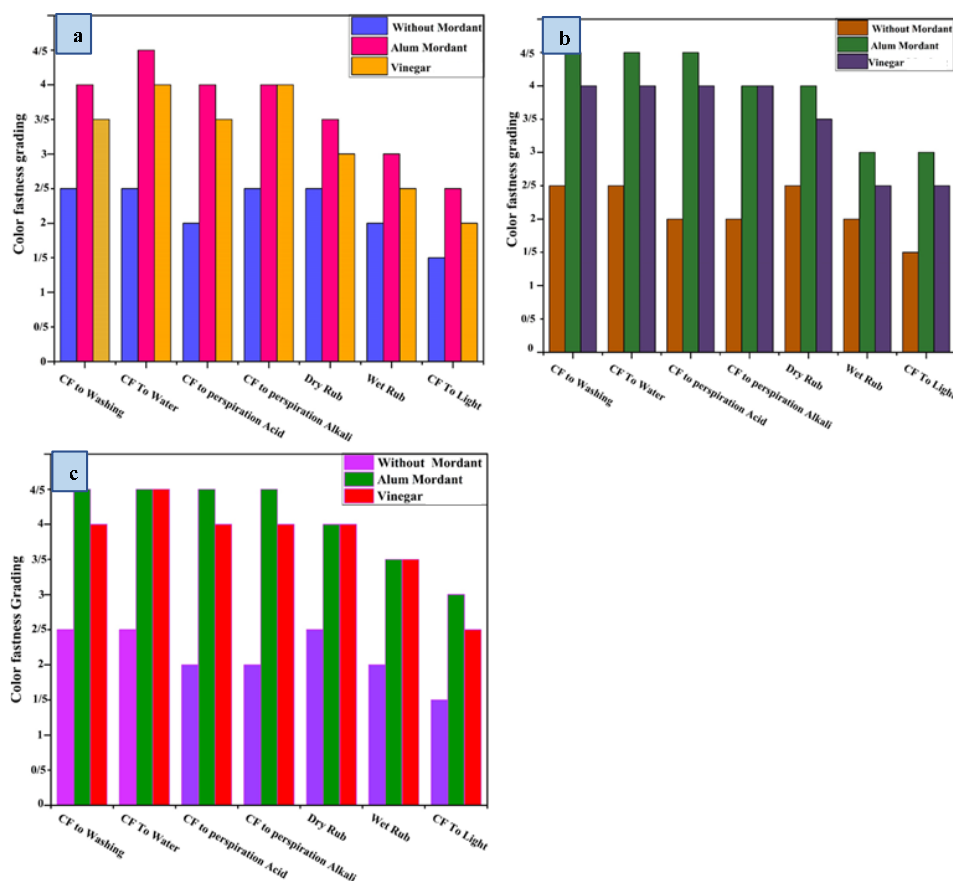


Figure 10. Color fastness gradings against washing, water, perspiration, rubbing, and light for (a) 2% shade, (b) 3% shade, and

4. CONCLUSIONS

This study demonstrates the potential of *Cocos nucifera* peel extract as a sustainable and eco-friendly natural dye source for polyester fabric. Although polyester is difficult to dye with natural extracts due to its hydrophobic structure, acceptable shade depth and color fastness were achieved through suitable dyeing and mordanting conditions. Among the tested conditions, alum-mordanted dyed fabric showed the best performance in terms of shade depth, evenness, and overall color fastness compared with vinegar-assisted and non-mordanted dyeing.

The findings suggest that alum can improve the interaction between coconut peel dye and polyester fiber, supporting better dye fixation and fastness properties. The use of coconut peel waste also indicates a promising approach for reducing dependence on synthetic dyes and promoting sustainable textile processing.

However, this study has some limitations. FTIR and SEM analyses were performed only on the alum-mordanted dyed fabric because it showed the best dyeing performance. Therefore, direct comparison with vinegar-assisted, non-mordanted, and undyed polyester samples was not possible. In addition, replicate measurements, standard deviation, and statistical significance tests such as ANOVA were not performed. Future studies should include FT-IR and SEM analyses of all treated and untreated samples, along with statistical analysis, to validate the findings more strongly.

AUTHORSHIP CONTRIBUTION STATEMENT

Prabir Kumar Das: Design project, raw materials collection, conducted the research experiments, processed data, drafted the manuscript; Md. Golam Mortuza Limon and Raju Kumar Das: investigation of data, visualization, writing-review, and editing, and Md. Khayrul Islam: project design, data calculation, methodology, supervision, project administration, writing, review, and editing. All authors have read and agreed to the published version of the manuscript.

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AI USAGE STATEMENT

Some of the content in this manuscript was drafted or improved using artificial intelligence tools on an as-needed basis during writing and language improvement. The authors then examined and fact-checked the AI-assisted content, as well as refining it manually. The authors assume full responsibility for the accuracy and final contents of the manuscript.

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