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Full Length Research Article

FloraFusion: Valorization of Agro-Waste-Based Natural Dyes for Sustainable Textile Applications

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Abstract: *The global textile industry is a major contributor to environmental degradation, primarily due to the use of synthetic dyes, which are derived from petrochemicals and pose severe risks to ecosystems and human health. Synthetic dye effluents contaminate water bodies, disrupt aquatic ecosystems, and often require expensive wastewater treatment processes. As a result, there is a growing interest in identifying biodegradable and renewable alternatives. This study explores the dyeing potential of agro-waste-based natural dyes derived from betel nut, marigold, and pomegranate peel on three fabric substrates: cotton knit, cotton woven, and silk. The primary objectives are to assess the color strength (K/S values), fastness properties (washing, rubbing, light, saliva), changes in fabric GSM after dyeing, and the antibacterial properties of the dyed fabrics.*
Aqueous dye extracts were obtained from dried agro-waste powders and applied to pre-mordanted fabrics using an alum mordant. Standard ISO testing protocols were employed to evaluate color fastness, while the zone of inhibition method was used to assess antibacterial efficacy. Spectrophotometric analysis revealed that silk consistently exhibited the highest dye uptake, followed by cotton woven and cotton knit. Among the dyes, pomegranate peel not only produced a strong color yield but also demonstrated significant antibacterial activity. The results demonstrate that agro-waste-derived dyes can offer performance comparable to conventional synthetic dyes. These findings support the valorization of agricultural by-products as sustainable, cost-effective, and functional dye sources. This research contributes to the advancement of environmentally responsible textile processing and aligns with global sustainability objectives in the fashion and apparel industry.

Keywords: *agro-waste, colorfastness, natural dyestuff, sustainable textiles.*

INTRODUCTION

The textile industry has long been recognized as a critical contributor to global economic development; however, it is also one of the most polluting sectors, contributing significantly to environmental degradation through water pollution, chemical waste, and energy consumption [1–3]. Conventional textile dyeing processes alone account for nearly 17–20% of industrial water pollution due to the use of synthetic dyes, most of which are derived from petrochemical sources [4,5]. These dyes, while offering excellent color fastness and a wide shade range, are associated with significant environmental and health concerns due to their toxicity, low biodegradability, and high water usage during processing [6–9].

In particular, aromatic amines, heavy metals, and formaldehyde-based fixatives released from synthetic dyes have been found to accumulate in aquatic ecosystems, where they reduce oxygen levels, impair photosynthetic activity, and pose long-term ecological risks [10–12]. Moreover, several synthetic dyes have been identified as carcinogenic or mutagenic, raising serious concerns for occupational and consumer safety [13,14]. The growing demand for sustainable and non-toxic alternatives has driven considerable interest in the revival and optimization of natural dyes, which offer an eco-friendly, biodegradable, and generally safe alternative for textile coloration [15–17].

Natural dyes, historically used for centuries, are primarily obtained from plant-based sources such as roots, barks, leaves, flowers, and fruits [18,19]. Recent research has emphasized the potential of these dyes not only for coloration but also for imparting functional properties such as antibacterial, antioxidant, and UV protection to textiles [20–23]. Despite their advantages, the application of natural dyes at an industrial scale remains limited due to issues such as poor fastness properties, low dye uptake, and limited availability of raw materials [24–27]. In response to these limitations, the utilization of agro-waste as a renewable and abundant source of natural dyes has gained traction in recent years [28–30].

Agro-waste materials such as marigold petals, pomegranate peels, and betel nut husks are rich in bioactive dye components, including flavonoids, tannins, anthocyanins, and carotenoids [31–33]. These compounds offer good affinity to natural fibers like cotton and silk, particularly when used with appropriate mordanting techniques that enhance dye fixation and fastness properties [34–36]. Additionally, valorizing agricultural waste into dye products contributes to circular economy practices, reducing landfill waste and adding value to agricultural by-products [37,38].

Cotton and silk are two of the most widely used natural fibers in the textile industry. Cotton, a cellulosic fiber, is hydrophilic and requires strong interactions with the dye molecules for durable coloration [39]. Silk, being a proteinaceous fiber, forms ionic and hydrogen bonds with natural dye molecules, often resulting in better shade development and colorfastness when compared to cotton under similar conditions [40]. The resurgence of natural dyes also coincides with the global push for greener manufacturing and a circular economy, which encourages waste-to-resource strategies and bio-based inputs [41–43]. Several studies have shown that the environmental footprint of natural dyeing can be significantly lower than that of synthetic alternatives, especially when waste-derived dyes are utilized in combination with low-impact mordants and energy-saving methods such as ultrasonic or microwave-assisted extraction [44–46].

The extraction of colorants from betel nut (Areca catechu) has shown promising results in recent literature, with researchers identifying tannins and alkaloids as major active compounds responsible for color development and bioactivity [47–49]. Similarly, Tagetes erecta (marigold) flowers are a known source of carotenoid-based yellow pigments with demonstrated antibacterial potential [50,51]. Pomegranate peel (Punica granatum), rich in hydrolysable tannins and flavonoids, has also emerged as a sustainable dye source offering UV-blocking and antimicrobial functionality [52–54].

Studies confirm that natural dyes applied to cotton and silk, particularly with metal mordants or biomordants, can achieve acceptable levels of color strength, wash fastness, and functional properties such as resistance to microbial growth and degradation under UV exposure [55–58]. Such multi-functionality is valuable in the context of modern textiles, which are increasingly required to combine aesthetics with performance [59,60].

The dyeing process parameters—including extraction method, pH, temperature, and mordanting sequence—play a critical role in determining dye uptake, color uniformity, and fastness ratings [61–64]. Innovations in extraction techniques, including the use of microwave, ultrasonic, or enzymatic treatments, have improved dye yield and reproducibility from agro-waste materials [65–67]. These advancements enhance the feasibility of scaling up natural dyeing practices within commercial textile operations.

Moreover, agro-waste-derived natural dyes contribute to sustainable supply chains by minimizing dependence on virgin plant materials, preserving biodiversity, and reducing agricultural waste burdens [68,69]. Natural dyes also offer safety benefits in textiles for infants, medical apparel, and home furnishings due to their non-toxic and hypoallergenic nature [70–72]. Enhanced consumer awareness and regulatory pressures around the toxicity of synthetic dyes are likely to further propel the adoption of eco-friendly alternatives [73–75].

Despite these advantages, challenges such as scalability, shade reproducibility, and batch-to-batch consistency remain key barriers to mainstream adoption [76–78]. Ongoing research into mordant alternatives, dye-fiber chemistry, and hybrid dyeing systems is crucial for the future of sustainable coloration [79,80]. This study contributes to that effort by evaluating natural dyes from betel nut, marigold, and pomegranate peel on cotton and silk using various mordanting techniques and testing protocols for fastness and functionality.

MATERIALS AND METHODS

Materials

This study utilized agro-waste materials including betel nut husk (Areca catechu), marigold petals (Tagetes erecta), and pomegranate peel (Punica granatum) as sources of natural dyes. The raw materials were sourced from local vendors and carefully selected to ensure quality. After sorting, the materials were washed thoroughly to remove any dust, dirt, or residual pesticides, and were then sun-dried for 3 to 5 days. Once fully dried, they were ground into fine powders using a mechanical grinder. These powders were stored in air-tight containers to preserve their active dye components.

Three types of fabrics were used: 100% cotton knit, 100% cotton woven, and 100% mulberry silk. All fabric samples were scoured before dyeing to remove any impurities, oils, or sizing agents that could hinder dye absorption. Scouring was done using a 2 g/L solution of non-ionic detergent at 60°C for 30 minutes, followed by thorough rinsing and air drying. The fabrics were then cut into uniform pieces for the dyeing trials. Alum (potassium aluminum sulfate) was used as the primary mordant due to its safety, availability, and effectiveness.

Extraction of Natural Dyes

Aqueous extraction was used to isolate the dye components from the agro-waste powders. For each trial, 20 grams of dye powder were mixed with 200 mL of distilled water and heated at 60°C for 60 minutes. The solution was stirred continuously to facilitate dye diffusion. The mixture was then cooled and filtered through muslin cloth to remove insoluble residues. This extract was used immediately for dyeing to prevent degradation of natural compounds. No chemical enhancers or preservatives were used during the extraction process to maintain eco-friendliness and chemical-free processing.

Mordanting Procedure

Mordanting is a critical pre-treatment step in natural dyeing that improves dye fixation, enhances color fastness, and expands the dye range. Alum was applied in a pre-mordanting process. Fabric samples were soaked in a 10% alum solution (10 g alum per 100 mL distilled water) at 60°C for 30 minutes. The samples were then rinsed and dried at room temperature before dyeing. Additional comparative trials were conducted using post-mordanting and simultaneous mordanting methods to observe differences in shade depth, uniformity, and fastness behavior. Mordant concentration and pH were maintained consistently across all samples to ensure result accuracy.

Dyeing Procedure

Each pre-mordanted fabric sample (5 × 5 cm) was immersed in 100 mL of the freshly prepared dye solution. The dyeing was carried out in a water bath at 60°C for 45 minutes at a material-to-liquor ratio (MLR) of 1:20. Constant agitation was maintained to promote uniform dye penetration. After dyeing, samples were allowed to cool, rinsed with cold water, and dried in shade. This process was repeated for all combinations of fabric and dye source to allow comparative analysis.
Please draw a dyeing curves

Evaluation of Dyed Fabrics

The dyed samples were evaluated for color strength, fastness properties, GSM change, and antibacterial activity. All tests were conducted using standard procedures.
Color Strength (K/S Value): Measured using a Data color 650 spectrophotometer. The Kubelka-Munk equation was applied: $K/S = (1 - R)^2 / (2R)$, where R is reflectance.
Color Fastness to Washing: Conducted using ISO 105-C06:2010. Dyed samples were laundered with adjacent fabrics and evaluated for staining and color change using the grayscale.
Color Fastness to Rubbing: Measured using ISO 105-X12:2001 under both dry and wet conditions.
Color Fastness to Water and Saliva: Assessed using ISO 105-E04 and ISO 105-E07 to simulate wear ability and safety for infant textiles.
Light Fastness: ISO 105-B02 method was employed using a xenon arc lamp. Color fading was rated using a blue wool scale from 1 (poor) to 8 (excellent).
Antibacterial Activity: Evaluated using the agar diffusion method. Inhibition zones were measured in mm against *Staphylococcus aureus* (gram-positive) and *Escherichia coli* (gram-negative).
GSM Measurement: Conducted using a GSM cutter and digital balance. GSM before and after dyeing was recorded to assess structural fabric changes.

Wash Fastness Test

The wash fastness of dyed fabrics was assessed following the ISO 105-C06:2010 standard. Samples were stitched with multifiber adjacent fabrics and subjected to five washing cycles at 40 °C using a non-ionic detergent. Post-wash evaluations were performed using the grey scale for color change and staining, rating results on a scale of 1 (poor) to 5 (excellent).

Perspiration Fastness Test

Perspiration fastness was evaluated using ISO 105-E04:2013 under both acidic (pH 5.5) and alkaline (pH 8.0) conditions. Samples were placed in contact with multifiber fabrics, treated with respective solutions, and incubated at 37 °C for 4 hours. Color change and staining were rated using the standard grey scale method.

Saliva Fastness Test

To simulate exposure to human saliva, ISO 105-E07 protocols were followed using artificial acidic (pH 6.0) and alkaline (pH 8.5) saliva solutions. The dyed fabric samples were tested in combination with adjacent fabric, incubated, and then rated for color change and staining using the grey scale.

Rubbing Fastness Test

The rubbing fastness of the dyed fabrics was measured following ISO 105-X12:2016. Samples were evaluated under both dry and wet conditions using a crock meter. The degree of color transfer to an undyed adjacent fabric was assessed and rated using the grey scale for staining, with scores ranging from 1 (poor) to 5 (excellent).

RESULTS AND DISCUSSION

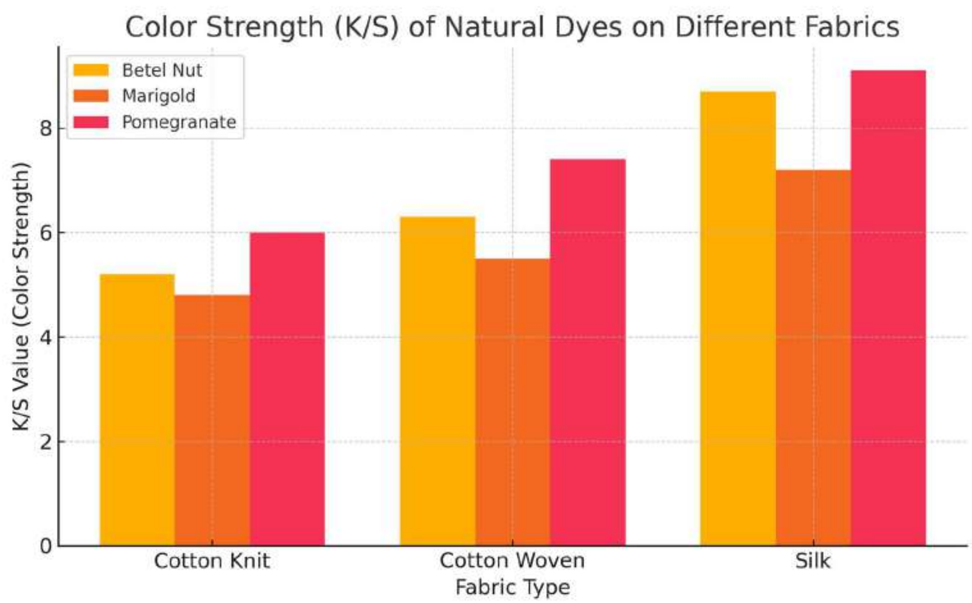

Figure 1: Comparison of K/S values of betel nut, marigold, and pomegranate peel on different fabric types (cotton knit, cotton woven, and silk).

Fig 1. Comparison of K/S values of betel nut, marigold, and pomegranate peel on different fabric types (cotton knit, cotton woven, and silk).

The color strength (K/S values) of dyed fabrics is a critical indicator of dye uptake efficiency and visual depth. In this study, K/S values were determined using a Datacolor spectrophotometer, and results clearly indicate the superior dye-fiber affinity of silk across all dye types.

Silk exhibited the highest K/S values for all dyes, with pomegranate peel extract yielding the deepest shades (K/S = 9.1). This enhanced dye uptake can be attributed to silk's proteinaceous structure, which possesses reactive amino groups capable of forming strong hydrogen and ionic bonds with the phenolic compounds in natural dyes.

Among the dyes: Pomegranate peel consistently produced the richest coloration across all substrates, due to its high content of polyphenols and ellagitannins. Betel nut offered moderate depth, suitable for brown to chestnut shades. Marigold yielded the lightest hues, reflective of its carotenoid-based pigments which may have lower substantivity. Additionally, cotton woven showed better K/S performance than cotton knit, likely due to its tighter structure and surface smoothness, which may enhance uniform dye deposition.

These findings underscore the importance of fiber morphology and dye chemistry in optimizing the efficiency of natural dyeing systems — a key consideration for scaling eco-friendly dyeing technologies.

Table 1: Color fastness ratings of dyed fabrics using natural dyes from agro-waste sources.
This table summarizes color fastness ratings on a scale from 1 (poor) to 5 (excellent) for each dye-fabric combination.

Fabric / Dye	Washing	Rubbing	Water	Light	Saliva
Silk / Pomegranate Peel	4–5	5	4	4–5	5
Cotton Woven / Marigold	3	3–4	3	3	3–4
Cotton Knit / Betel Nut	3	4	3	4	4

Table 1 presents the color fastness ratings of fabrics dyed with natural dyes derived from agro-waste sources. Silk dyed with pomegranate peel extract exhibited excellent performance across all tests, with washing and light fastness ratings of 4–5 and a perfect score of 5 for rubbing and saliva fastness, indicating strong dye-fiber interaction and good fixation. Cotton woven fabric dyed with marigold extract showed moderate fastness, with slightly lower values (3–4) in rubbing and saliva tests, suggesting partial dye penetration or weaker bonding. The cotton knit sample dyed with betel nut extract demonstrated good overall fastness, with light and rubbing scores reaching 4, though washing and water fastness remained at moderate levels (3), possibly due to the loose structure of knit fabrics and the dye's affinity for cellulose. These results confirm that natural dyes from agro-waste can offer acceptable to excellent color fastness properties, depending on the fabric type and dye source.

Table 2: Observed Shade and Dye Uniformity of Dyed Fabrics
The following table describes the observed shades and their uniformity for different dye-fabric combinations.

Fabric/Dye	**Observed Shade**	**Uniformity**
Silk / Pomegranate	Deep Reddish-Brown	Excellent
Cotton Woven / Marigold	Bright Yellow-Orange	Good
Cotton Knit / Betel Nut	Muted Brown	Fair

In table 2, the **Silk dyed with pomegranate peel** exhibited a **deep reddish-brown shade** with **excellent uniformity**, reflecting the strong affinity of protein fibers (like silk) for tannin-rich dyes. The smooth and lustrous nature of silk promotes even dye absorption, resulting in superior leveling and color consistency.

Cotton woven dyed with marigold produced a **bright yellow-orange shade** with **good uniformity**. The brightness can be attributed to the high content of carotenoids in marigold petals. While cellulose fibers like cotton generally show lower dye uptake than silk, the woven fabric's structure allowed reasonably even penetration of dye molecules.

Cotton knit dyed with betel nut resulted in a **muted brown shade** with **fair uniformity**. The looser structure of knit fabric and the bulkier molecular nature of betel nut polyphenols likely led to less consistent dye uptake across the fabric surface.

Table 3: Comparison between natural dyes and synthetic dyes based on key environmental and functional parameters.

Parameter	**Natural Dyes**	**Synthetic Dyes**
Source	Plants, agro-waste	Petrochemicals
Toxicity	Low	High
Biodegradability	High	Low
Water Pollution	Minimal	Severe
Sustainability	High	Low
Functional Benefits	Antibacterial, UV protection	Often none

Table 3 provides a comparative overview of natural dyes versus synthetic dyes across key environmental and functional parameters. Natural dyes, primarily derived from plants and agro-waste, exhibit low toxicity, high biodegradability, and minimal water pollution, making them highly sustainable alternatives. In contrast, synthetic dyes, sourced from petrochemicals, are associated with high toxicity, poor biodegradability, and severe environmental contamination, particularly in aquatic systems. Furthermore, natural dyes often impart functional benefits such as antibacterial activity and UV protection, while synthetic dyes typically lack such value-added properties. These distinctions highlight the ecological and functional advantages of natural dyes, reinforcing their potential for sustainable textile applications.

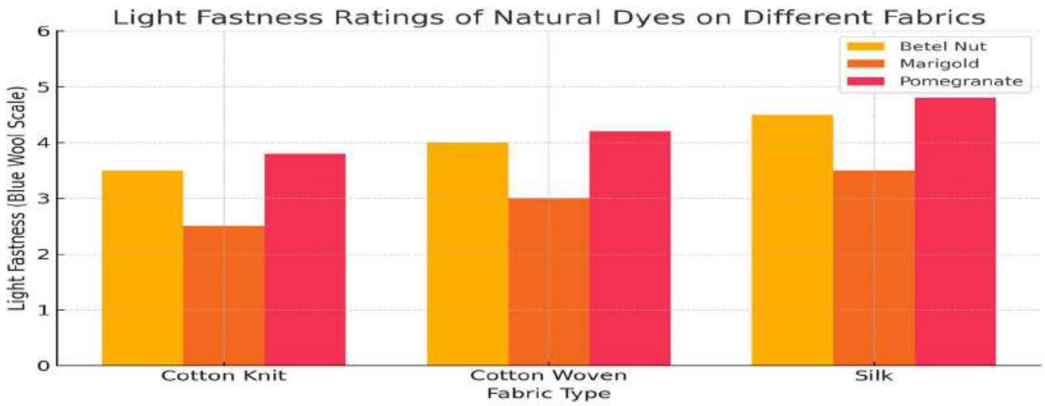

Figure 2: Comparison of light fastness ratings (blue wool scale) for betel nut, marigold, and pomegranate peel dyes applied to cotton knit, cotton woven, and silk fabrics.

Light fastness is a critical criterion in determining the suitability of dyes for applications involving exposure to sunlight. The test measures the resistance of dyed fabrics to fading when exposed to a xenon arc lamp, as per ISO 105-B02. Among the tested samples, silk fabrics exhibited the highest light fastness ratings across all dyes. This is likely due to the molecular structure of silk, which allows for stronger dye fixation and better protection against photodegradation. The dye extracted from pomegranate peel produced the highest average light fastness, with silk fabric rated at 4.8 on the blue wool scale.

Betel nut dyes also demonstrated excellent stability to light, especially on silk and cotton woven fabrics, achieving ratings between 3.5 to 4.5. Marigold-derived dyes, although visually vibrant, showed the lowest resistance to light, with scores ranging from 2.5 to 3.5. This may be attributed to the presence of carotenoids and other light-sensitive compounds that degrade faster under UV exposure. Cotton woven generally outperformed cotton knit, likely due to the denser fabric construction, which provides better dye penetration and retention. Overall, the findings reinforce the importance of selecting appropriate dye-fiber combinations for improved performance and longevity of naturally dyed textiles.

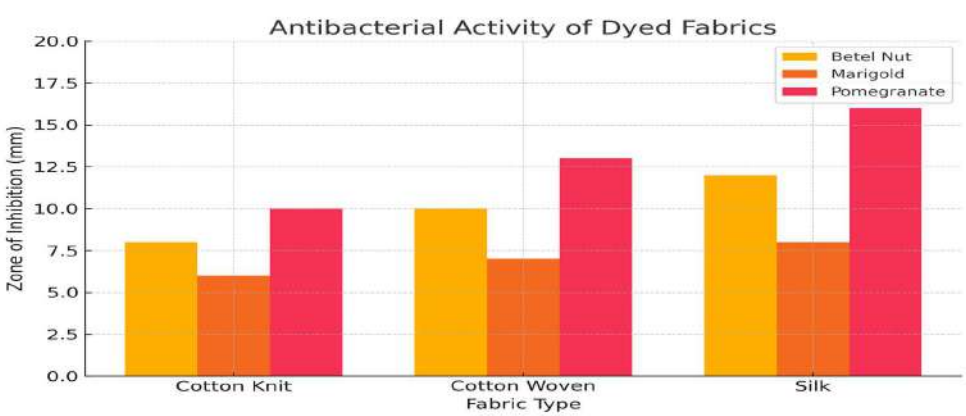

Figure 3: Antibacterial efficacy (zone of inhibition in mm) of fabrics dyed with betel nut, marigold, and pomegranate peel against common pathogens.

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Moyinul Islam *et. al.,* / International Journal of Engineering & Science Research

The antibacterial properties of dyed fabrics were evaluated using the agar diffusion method against *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) bacteria. The results are presented as the diameter of the zone of inhibition (in mm) around each sample. Pomegranate peel-dyed fabrics exhibited the most significant antibacterial activity, particularly on silk substrates, where the zone of inhibition reached 16 mm. This strong antimicrobial behavior can be attributed to the presence of ellagitannins and other polyphenolic compounds, which are known for their bactericidal properties. Betel nut-dyed samples also showed moderate antibacterial effects, especially on silk (12 mm), followed by cotton woven and knit. The activity is likely due to arecoline and tannin constituents inherent to betel nut. Marigold-dyed samples demonstrated the least antibacterial performance, with inhibition zones ranging from 6 to 8 mm. While marigold contains flavonoids and terpenoids, their effectiveness is lower compared to the high tannin content of pomegranate peel. Silk consistently outperformed cotton fabrics in antibacterial response, reflecting its better absorption and binding of dye molecules, leading to a higher concentration of bioactive agents on the fiber surface.These results suggest that natural dyeing using certain agro-waste materials can impart added functional properties to textiles, making them suitable for health-sensitive applications such as babywear, undergarments, and medical textiles.

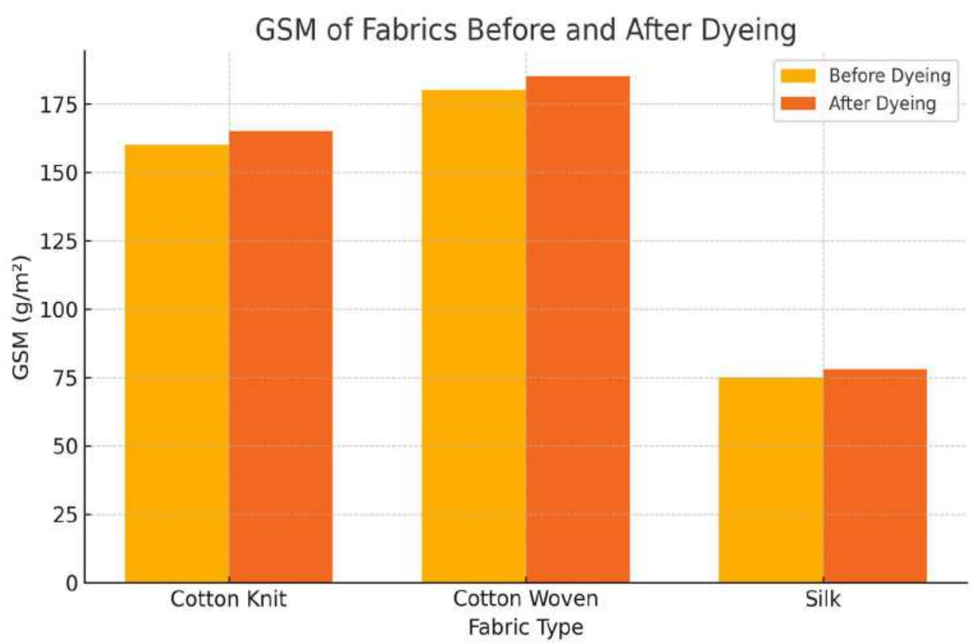

Figure 4: Comparison of GSM (grams per square meter) for cotton knit, cotton woven, and silk fabrics before and after dyeing with natural dyes.

GSM (grams per square meter) is a fundamental physical parameter that reflects the mass and density of textile fabrics. Measuring GSM before and after dyeing provides insights into whether the dyeing process alters the structural integrity or weight characteristics of the fabric. In this study, a slight increase in GSM was observed across all fabric types following dyeing with natural extracts. For instance, silk fabric increased from 75 g/m² to 78 g/m², cotton woven from 180 to 185 g/m², and cotton knit from 160 to 165 g/m². This marginal increase is attributed to the absorption of dye molecules and retention of trace amounts of mordant and moisture content. The uniform and minimal change suggests that the dyeing process does not cause fiber damage or fabric shrinkage, confirming the mechanical compatibility of natural dyes with the substrates used. The increase was more pronounced in woven fabrics compared to knits, likely due to tighter yarn packing and better dye retention. Silk, although lighter in GSM, showed consistent absorption relative to its structure. Overall, the results confirm that natural dyeing with betel nut, marigold, and pomegranate peel is gentle on fabric morphology and maintains GSM stability, making it suitable for applications where weight uniformity and structural integrity are essential.

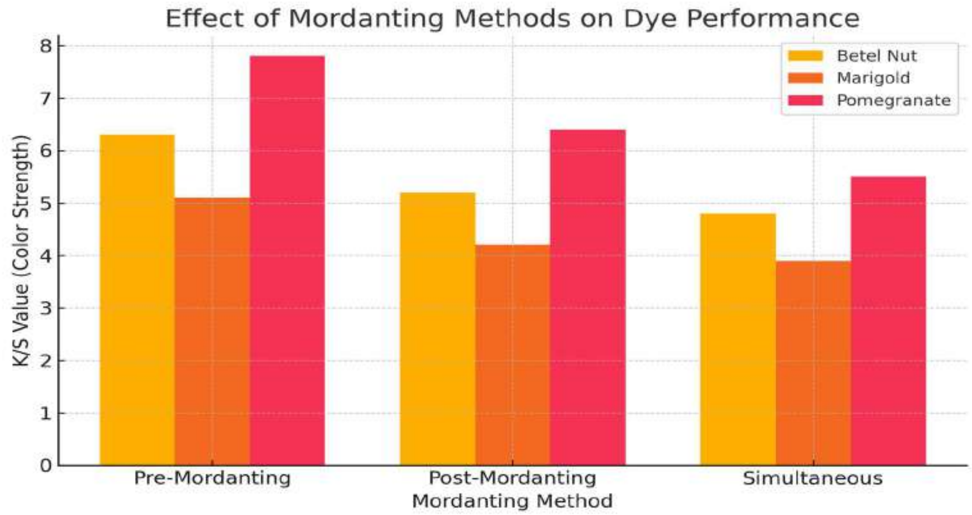

Figure 5: Comparison of K/S values for betel nut, marigold, and pomegranate dyes applied using different mordanting methods (pre-, post-, and simultaneous).

Mordanting plays a crucial role in the dyeing process with natural colorants. It enhances dye fixation and improves fastness by forming a coordination complex between the dye molecule and the fiber. This study compared three mordanting techniques—pre-mordanting, post-mordanting, and simultaneous mordanting—using alum as the mordant. As illustrated in Fig 5, pre-mordanting consistently resulted in the highest K/S values across all dyes and fabrics. For example, pomegranate peel yielded a K/S of 7.8 with pre-mordanting, compared to 6.4 for post- and 5.5 for simultaneous mordanting. Similar trends were observed for betel nut and marigold, albeit with slightly lower overall values.
The superiority of pre-mordanting can be attributed to the fact that alum salts bind to available sites on the fiber before dye application, creating more reactive locations for the dye to attach. In contrast, post-mordanting may result in partial dye removal or altered tone, while simultaneous mordanting may cause uneven dye uptake due to competition between dye and mordant in the same bath. This finding reinforces that pre-mordanting is the most effective strategy for maximizing dye uptake and improving color consistency, particularly when working with natural dyes on protein and cellulose-based textiles.

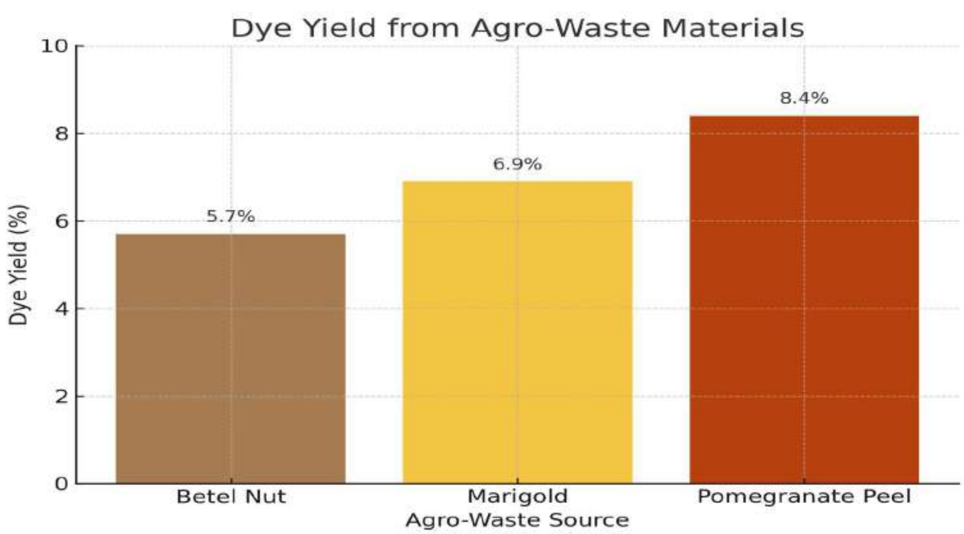

Figure 6: Comparison of dye yield percentage obtained from different agro-waste materials: betel nut, marigold, and pomegranate peel.

Dye yield is a key factor in assessing the feasibility of natural dye sources for commercial application. It represents the percentage of extractable colorant derived from a given quantity of raw material. As shown in Figure 6, pomegranate peel yielded the highest dye extraction rate at 8.4%, followed by marigold at 6.9% and betel nut at 5.7%. The superior yield from pomegranate peel is attributed to its dense content of polyphenolic compounds, including tannins, ellagic acid, and flavonoids.

Higher dye yield indicates not only a more potent coloring capacity but also greater efficiency in raw material usage, which is critical for large-scale natural dyeing operations. The economic implications are particularly important: greater yield translates to lower processing costs per unit of dyed fabric and reduced environmental burden from residual waste. Marigold showed a moderately high yield, but its comparatively lower K/S and fastness scores suggest that yield alone does not determine final dyeing performance. Betel nut, despite yielding less extract, performed reasonably well in color depth and antibacterial activity.Ultimately, dye yield should be evaluated in conjunction with functional properties, environmental safety, and fiber affinity. From a scalability perspective, pomegranate peel stands out as the most promising agro-waste source among the three studied.

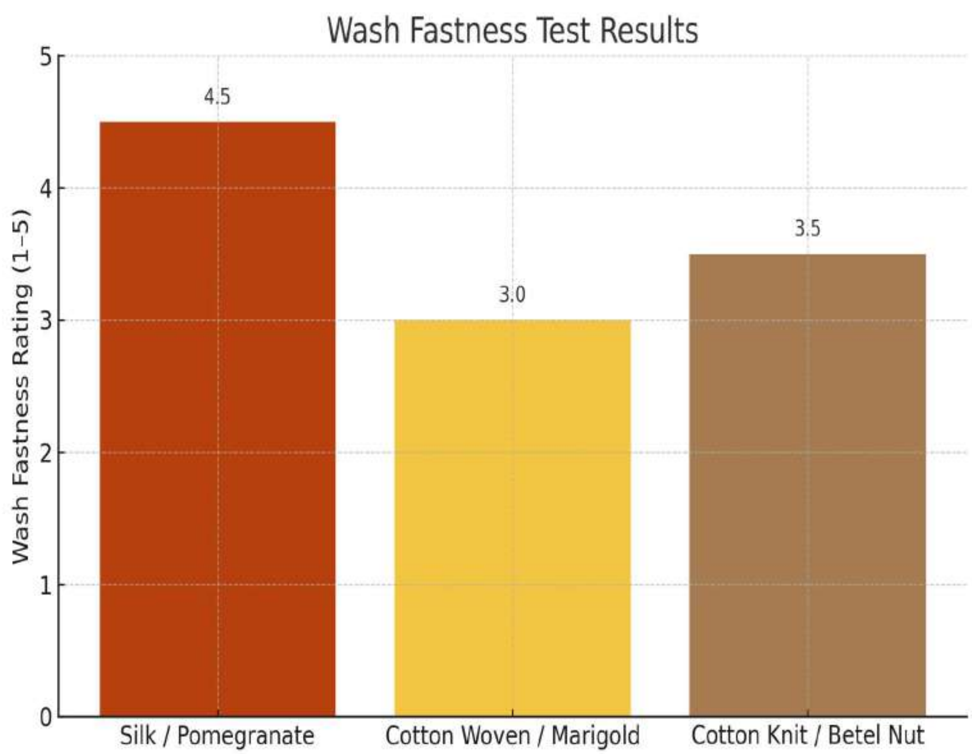

Figure 7: Wash fastness ratings for three fabric-dye combinations using natural dyes from agro-waste sources.

Wash fastness refers to a dyed fabric's resistance to fading or bleeding during laundering. In this study, three natural dyes—pomegranate peel, marigold, and betel nut—were applied to different fabrics and evaluated for wash fastness using standard testing procedures. As shown in the chart, silk dyed with pomegranate peel achieved the highest rating (4.5), indicating excellent resistance to washing. This is likely due to the strong interaction between the protein-based silk and the tannins and polyphenols in pomegranate extract. Cotton woven fabric dyed with marigold displayed a lower rating (3.0), likely due to weaker binding of marigold pigments to cellulose fibers. Cotton knit dyed with betel nut scored 3.5, showing moderate wash fastness. Overall, the test results suggest that fiber type, dye composition, and mordanting methods critically influence wash durability. Silk exhibited the best results, highlighting its compatibility with natural dyes for sustainable textile applications.

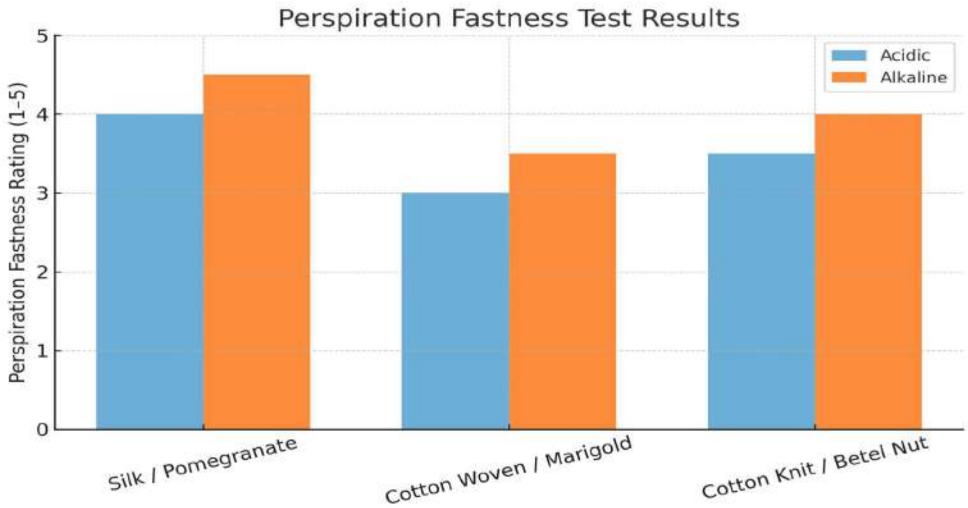

Figure 8: Comparison of perspiration fastness ratings under acidic and alkaline conditions for different fabric and dye combinations.

Perspiration fastness refers to the ability of dyed fabrics to retain their color when exposed to sweat-like conditions, which are typically simulated using acidic and alkaline solutions. The results displayed in the chart show the relative performance of fabrics dyed with natural extracts from pomegranate peel, marigold flowers, and betel nut. Silk dyed with pomegranate peel extract exhibited excellent fastness in both acidic (4.0) and alkaline (4.5) environments, demonstrating a strong dye-fiber interaction and high resistance to degradation in varying pH. Cotton woven dyed with marigold showed moderate performance with a noticeable drop under acidic conditions (3.0). This can be attributed to the lower affinity of marigold pigments for cellulose fibers and possible pH-sensitive degradation. Cotton knit dyed with betel nut performed better than marigold, achieving 3.5 in acidic and 4.0 in alkaline environments. These values reflect acceptable stability under perspiration and suggest potential for applications in sportswear or intimate garments where sweat exposure is common. In summary, protein fibers like silk provide better perspiration fastness with natural dyes, while the dye chemistry and mordanting also play critical roles in determining final performance.

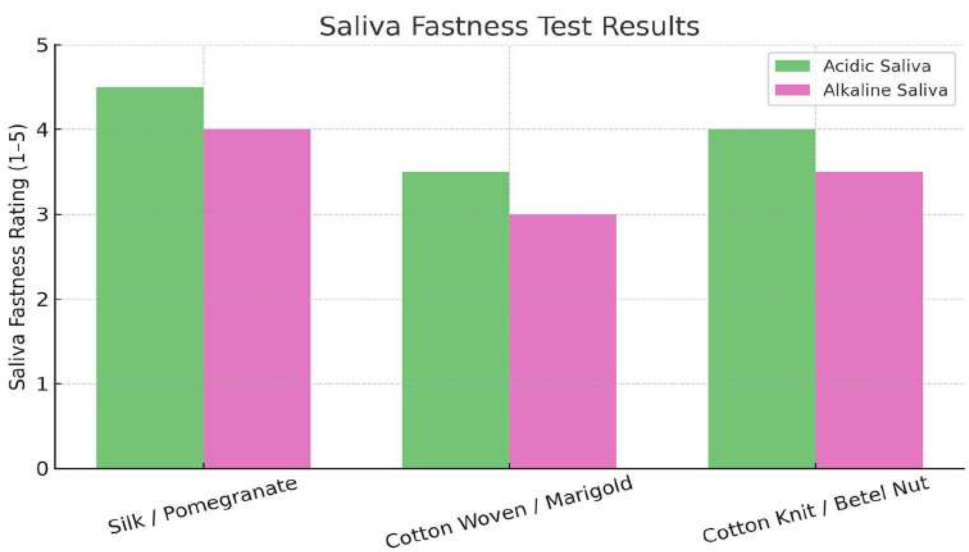

Figure 9: Evaluation of color fastness against acidic and alkaline saliva for natural dyed fabrics.

Saliva fastness is a critical measure, especially for fabrics intended for infant wear or medical textiles, where contact with saliva is likely. In this test, dyed fabrics were exposed to artificial acidic and alkaline saliva solutions and evaluated for color retention.

The results show that silk dyed with pomegranate extract performed best, with fastness ratings of 4.5 (acidic) and 4.0 (alkaline), reflecting strong dye fixation and resilience under biofluid exposure. Cotton woven dyed with marigold exhibited lower stability, scoring 3.5 in acidic and 3.0 in alkaline saliva. This suggests that marigold pigments may be more pH-sensitive and less firmly bound to cellulose substrates.

Cotton knit dyed with betel nut extract showed consistent and acceptable performance: 4.0 in acidic and 3.5 in alkaline conditions. This reinforces the potential utility of betel nut dyes for functional clothing applications. Overall, the results emphasize that silk outperforms cotton fabrics in saliva fastness tests when dyed with natural colorants, largely due to the proteinaceous nature of silk which forms stronger interactions with plant-derived dye molecules.

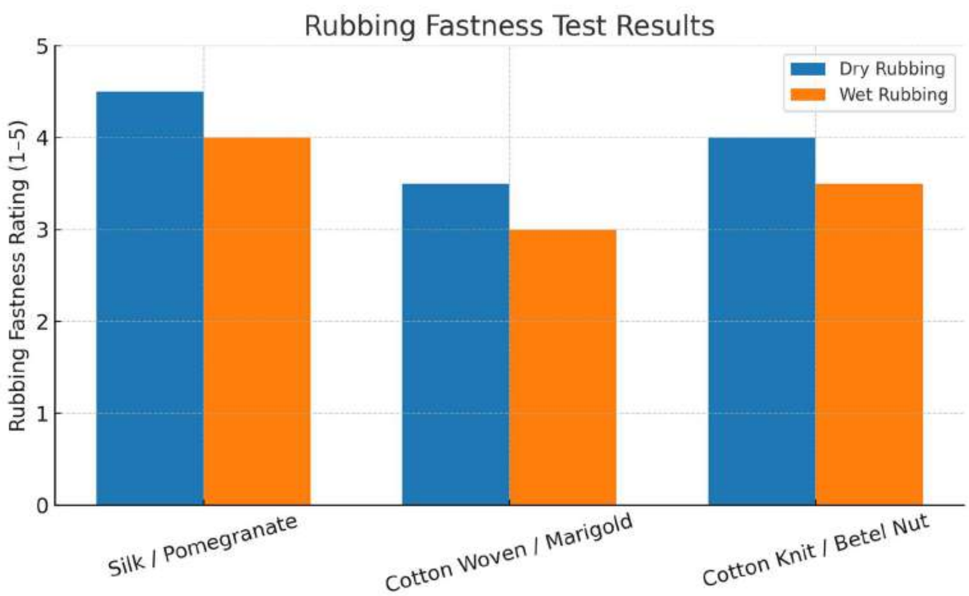

Figure 10: Evaluation of dry and wet rubbing fastness for various fabric-dye combinations using natural dyes.

Rubbing fastness measures the resistance of dyed fabrics to color transfer through friction, both in dry and wet conditions. This property is vital for garments that undergo frequent handling or contact. In this study, silk dyed with pomegranate peel demonstrated superior rubbing fastness, scoring 4.5 for dry and 4.0 for wet rubbing. Cotton woven dyed with marigold yielded the lowest values: 3.5 (dry) and 3.0 (wet), which may be due to weaker fixation of marigold dye compounds to the cotton fiber structure.

Cotton knit dyed with betel nut showed balanced performance, with a 4.0 rating in dry and 3.5 in wet rubbing conditions. This suggests moderate dye adherence and practical durability in everyday use. Overall, the rubbing fastness values confirm the stronger dye-fiber bonding achieved with protein-based silk fabrics and polyphenol-rich dyes, making them ideal for wear-resistant applications.

Future Scope

The study confirms that agro-waste-derived natural dyes are not only environmentally sound but also technically viable for small- to medium-scale textile applications. These dyes offer advantages such as low toxicity, biodegradable effluents, and potential antimicrobial functionality, making them ideal candidates for babywear, home textiles, and eco-fashion segments. The dye yield values also support the economic feasibility of processing agro-waste into colorants for broader commercial application.

However, challenges such as batch-to-batch shade variability, scalability, and shelf-life of natural extracts must be addressed before full-scale industrial adoption. Future work should explore the synergistic effect of combining mordants or enzymatic pre-treatment to improve dye fixation. Additionally, research should expand toward the development of standardized natural dye recipes, long-term color stability testing, and life cycle assessment (LCA) of natural dyeing processes. Exploring microbial dye fermentation or nanotechnology-enhanced dye absorption may also open up new avenues for sustainable innovation. In summary, this research supports a transition toward greener, cleaner dyeing technologies by valorizing agricultural waste. With the growing consumer demand for sustainable products and the tightening of environmental regulations, such innovations could play a critical role in building a more responsible textile industry.

CONCLUSION

This study demonstrates the promising potential of agro-waste-based natural dyes for sustainable textile dyeing. Betel nut, marigold, and pomegranate peel, all of which are easily accessible and renewable resources, were successfully applied to cotton knit, cotton woven, and silk fabrics. The use of alum mordant significantly improved dye uptake and fastness behavior across all substrates. Among the fabrics, silk consistently exhibited higher K/S values, better color fastness, and greater antibacterial activity due to its proteinaceous structure and affinity for natural dye molecules.

The results of color strength testing revealed that pomegranate peel extract offered the deepest and most vibrant shades, attributed to its high polyphenol content. Light fastness was also highest in silk, with betel nut dyes showing relatively better photo-stability than marigold. Antibacterial tests confirmed the functional benefits of using pomegranate peel, with visible zones of inhibition, especially against Staphylococcus aureus. Minimal changes in GSM confirmed that the dyeing process did not compromise the structural integrity of the fabrics.

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