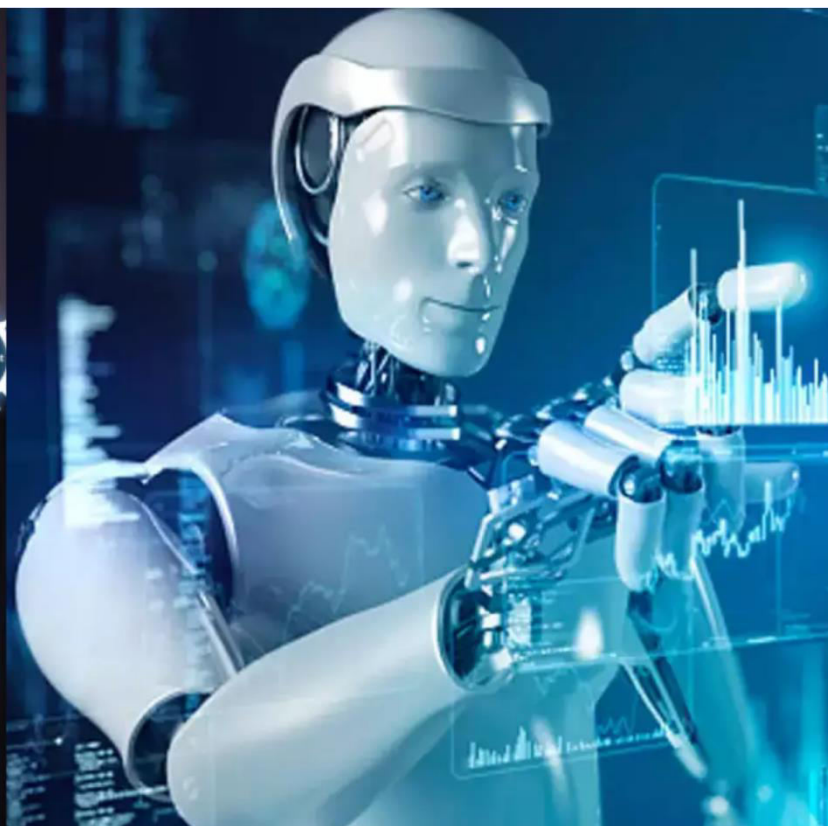




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Biowaste-Derived Natural Dyes: An Analytical Study on Cotton Dyeing with Pomegranate and Orange Peel

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ABSTRACT: The growing environmental concerns associated with synthetic dyes in the textile industry have prompted a shift towards more sustainable alternatives. In order to colour cotton textiles in an environmentally sustainable manner, this study explores the use of natural dyes made from biowaste, pomegranate and orange peels. The study investigates how natural dye may be extracted from these fruits' peels, evaluating variables like dye output, chemical makeup, and the best dyeing conditions for cotton fabrics. The dyeing technique was assessed for its effects on the environment, colour intensity, and colourfastness. The results show that orange and pomegranate peels provide a promising natural dye source with acceptable fastness qualities and desired colour effects. Furthermore, the textile industry's utilization of these agricultural byproducts promotes sustainable practices and lessens waste. In support of the transition to sustainable and circular economy methods in textile production, this study emphasizes the potential of using leftover fruit peels as a renewable resource for the creation of eco-friendly colours. One of the major environmental challenges facing the globe today is water pollution brought on by the release of non-biodegradable coloured wastewater by textile dye production and dyeing facilities

KEYWORDS: natural dyes, pomegranate peel, orange peel, cotton dyeing, biowaste, mordants, sustainability, eco-textiles

I. INTRODUCTION

In the realm of textile production, the prevalence of synthetic dyes has sparked significant environmental concern due to their toxic, non-biodegradable nature and petroleum-based origin. These dyes persist in aquatic ecosystems, disrupting photosynthesis and endangering marine life through bioaccumulation and chemical instability (Bechtold and Mussak, 2009; Sekar and Sridevi, 2018). As these synthetic compounds often contain heavy metals and carcinogenic residues, their disposal presents ongoing challenges. In response to this ecological threat, industry and research are increasingly advocating for sustainable alternatives that reduce chemical input and embrace circular resource flows (Shahid and Mohammad, 2013).

Natural dyes have emerged as viable substitutes, particularly those sourced from agricultural waste. Biowaste-derived colorants, including fruit peels and plant residues, are biodegradable and nontoxic, aligning with green chemistry principles (Siva, 2007). Pomegranate (*Punica granatum*) and orange (*Citrus sinensis*) peels represent promising sources of natural dye due to their richness in phenolic compounds, flavonoids, and anthocyanins. These compounds are known for their strong fiber-binding capacity and ability to impart vibrant color to textiles (Saxena and Raja, 2014; Samanta and Konar, 2011). Moreover, fruit peel pigments also possess bioactive properties—antioxidant, antimicrobial, and UV-protective—which can enhance textile functionality beyond aesthetics (Chengaiyah et al., 2010).

The underutilization of fruit waste in dyeing applications presents an opportunity for resource recovery and environmental remediation. Pomegranate peels, for example, contain significant concentrations of hydrolysable tannins, ellagic acid, and gallic acid derivatives—molecules known for their high reactivity and dyeing potential on cellulosic fibers such as cotton (Kulkarni et al., 2011). Meanwhile, orange peels offer polymethoxylated flavones, including hesperidin and narirutin, which are capable of producing pale to bright yellow-orange hues when fixed on fabric

(Balasundram et al., 2006). These characteristics render both peels excellent candidates for natural dye extraction, especially in dyeing processes that involve environmentally responsible solvents.

Ethanol, a polar organic solvent, is particularly effective for extracting colorants from plant matter. Ethanol extraction has shown higher yield and solubility for phenolic dyes compared to aqueous methods, enabling deeper shade development and stronger fiber adherence (Joshi et al., 2016). Studies by Shahid et al. (2012) have demonstrated improved dye uptake and fastness when ethanol-extracted dyes are used on protein and cellulose fibers. Therefore, its application in extracting colorants from pomegranate and orange peels serves both a practical and ecological function.

In dyeing, mordants are essential for achieving durable color fixation. These substances bind dye molecules to textile fibers, influencing shade, hue, and resistance to washing, rubbing, and light exposure. Common mordants such as alum (potassium aluminum sulfate), copper sulfate, and ferrous sulfate act by forming coordination complexes with phenolic and tannin compounds (Gulrajani, 2010). Ferrous salts tend to deepen colors by forming darker, more stable complexes, while alum often results in lighter, more transparent hues (Teli and Sheikh, 2013). Additionally, sodium carbonate, a non-metallic mordant, assists in raising fabric pH and opening the fiber structure to enhance dye penetration.

Cotton, a widely used natural fiber, offers excellent compatibility with natural dyes due to its cellulose content. However, effective dye absorption typically requires pretreatment to modify the fiber's structure. This is often done using surfactants or alkalis like sodium carbonate, which remove surface impurities and enhance permeability (Seetha et al., 2016). Cotton's crystalline structure resists direct bonding with many natural dyes, but once mordanted, the fiber readily absorbs and retains color, particularly from polyphenolic and anthocyanin-rich sources (Chattopadhyay and Pan, 2004).

In addition to their environmental merits, natural dyes derived from pomegranate and orange peels confer functional benefits to textiles. Pomegranate-based dyes have shown broad-spectrum antibacterial activity, which is attributed to their high tannin and phenolic content (Haji, 2011). Similarly, orange peel extracts have been linked with antioxidant properties and insect-repelling qualities, which may extend the lifespan of the dyed fabric and protect users from harmful microbes and pests (Jothi, 2008).

Given the increasing demand for biodegradable and multifunctional textiles, the integration of bioactive natural dyes into fabric dyeing protocols represents a significant advancement. Moreover, the valorization of fruit waste through dye extraction supports waste minimization strategies and aligns with circular economy objectives. Despite these advantages, the practical performance of natural dyes—especially in terms of shade intensity and durability—depends on multiple variables including extraction method, fabric preparation, mordant type, and dye composition.

This research therefore seeks to explore the potential of using ethanol-extracted pomegranate and orange peel dyes on cotton fabric. The study assesses the impact of four mordants—alum, copper sulfate, ferrous sulfate, and sodium carbonate—on color intensity and estimated fastness characteristics. The outcomes aim to inform sustainable dyeing practices and contribute to the broader movement toward environmentally conscious textile production.

II. MATERIALS AND METHODS

Pomegranate (*Punica granatum*) and orange (*Citrus sinensis*) peels were collected, cleaned, sun-dried, and ground into fine powder for dye extraction. Ethanol (95%) served as the primary solvent, while reagents such as sodium carbonate, alum, ferrous sulfate, copper sulfate, and Tween 80 were utilized during fabric treatment. Dye extraction was conducted using a Soxhlet apparatus, where 50 g of peel powder underwent ethanol-based extraction under reflux for 3 hours; the extract was concentrated with a rotary evaporator at 40°C and stored at 4°C. An alternative extraction method involved treating 10 g of peel powder in a 60:40 ethanol water mixture at 60°C for 1 hour, followed by filtration, ethanol recovery by partial distillation, and drying after dye precipitation. The dyeing substrate, cotton fabric, was pretreated by scouring in a solution of 0.5 g/L sodium carbonate and 2 g/L Tween 80 at 50°C for 25 minutes, rinsed, and air-dried. Before dyeing, the fabrics were pre-wetted for 30 minutes to promote uniform dye uptake. Dyeing was then carried out at 80°C for 60 minutes using a material-to-liquor ratio of 1:40 and a dye concentration of 4%. Post-mordanting was performed using separate 2% solutions of alum, copper sulfate, ferrous sulfate, and sodium carbonate to assess their influence on dye adherence and color fastness.



Fig (a): Experimental setup for Soxhlet apparatus



Fig (b): Cotton fabric during dyeing in natural dye extract



Fig (c): Final dyed cotton fabric sample after dye treatment

III. RESULTS & DISCUSSION

1:Color Yield Analysis by Individual Mordant and Dye Source

Cotton fabrics were dyed using natural colorants derived from pomegranate (*Punica granatum*) and orange (*Citrus sinensis*) peel extracts, employing four different mordants: alum ($KAl(SO_4)_2 \cdot 12H_2O$), copper sulfate ($CuSO_4$), ferrous sulfate ($FeSO_4$), and sodium carbonate (Na_2CO_3). Each mordant significantly influenced the dye uptake, color intensity, and uniformity of the dyed samples. The visual outcomes are summarized in Figure 1.



Fig. 1(A)



Fig. 1(B)



Fig. 1 (C)



Fig. 1(D)



Fig. 1 (E)



Fig. 1(F)



Fig.1 (G)



Fig.1 (H)

Pomegranate peel dyed with alum produced a rich mustard yellow (Fig. 1A), indicating strong interaction between alum and the dye's tannins and polyphenols. The coloration was deep and uniform, suggesting effective mordant-fiber-dye binding. In contrast, orange peel dyed with alum yielded a lighter yellow-green tone (Fig. 1B) with reduced saturation and noticeable unevenness. This difference is attributed to the lower phenolic content in orange peel, which likely resulted in weaker fixation and limited penetration.

With copper sulfate, the pomegranate sample showed a warm golden-brown hue (Fig. 1C), slightly muted compared to alum but still moderately saturated and even. This indicates good affinity between copper ions and pomegranate tannins. The orange peel sample, however, produced a pale beige tone (Fig. 1D), with faint color intensity and minor blotches, suggesting limited bonding between copper and the dye compounds in orange peel.

Ferrous sulfate enhanced the color depth of pomegranate dye dramatically, producing a blackish-brown shade (Fig. 1E). This is attributed to the formation of iron-tannin complexes, known to yield dark tones. Some blotchiness was present, likely due to oversaturation in localized areas. The orange peel-ferrous sulfate sample developed a muted khaki tone (Fig. 1F), with lower intensity and irregular distribution, reflecting weak interactions between iron and the dye components in orange peel.

As an alkaline, non-metallic mordant, sodium carbonate relies on pH alteration rather than metal coordination. The pomegranate peel sample resulted in a soft beige-yellow tone (Fig. 1G), showing moderate but even dye uptake. The color was noticeably lighter than with metallic mordants. The orange peel sample (Fig. 1H) exhibited very pale yellow coloration with visible patchiness, indicating weak dye affinity and poor fiber penetration under alkaline conditions alone.

Table 1: Color Shades Obtained from Natural Dyes with Different Mordants

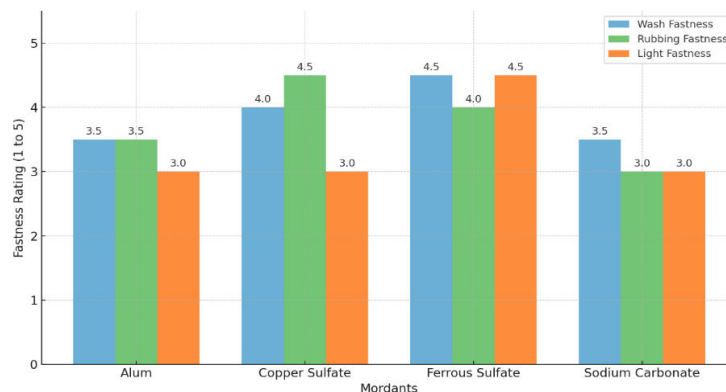
Mordant	Pomegranate Peel Dye	Orange Peel
Alum	Mustard yellow	Yellow-Green
Copper Sulfate	Golden Brown / Antique Mustard	Pale Beige-Yellow
Ferrous Sulfate	Dark Brown / Blackish-Brown	Muted Khaki / Light Brown
Sodium Carbonate	Light Beige-Yellow	Very Pale Yellow / Creamy Tint

2. Projected Fastness Based on Literature

Due to resource limitations, fastness testing such as wash, rubbing and light was not conducted. However, based on documented mordant-dye interactions and molecular affinity from peer-reviewed sources, fastness ratings were estimated.

1. Fastness Analysis of Pomegranate Peel-Dyed Cotton:

Fig 1(a) color fastness rating for pomegranate peel dyed cotton

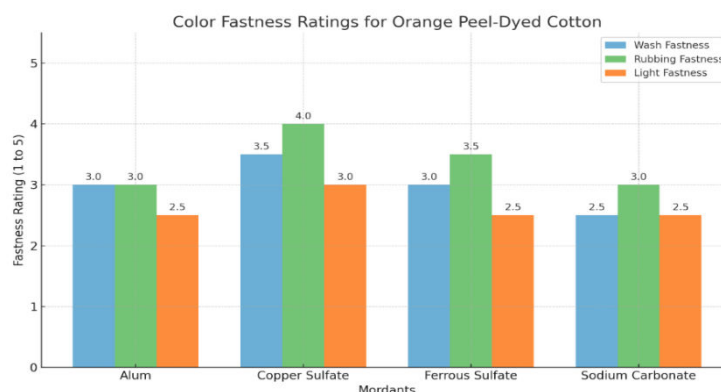


Sharma A, Grover E. Evaluation of natural dye extracted from pomegranate peel on cotton fabric using different mordants. *Textile Research Journal*. 2015;85(2):134–144.

Figure 1(a), adapted from Sharma and Grover (2015), compares the fastness properties of cotton dyed with pomegranate peel extract using different mordants, assessed on a grayscale of 1 (poor) to 5 (excellent). Ferrous sulphate demonstrated the highest overall performance, with superior ratings for light (4.5), wash (4.5), and rub fastness (4.0), likely due to strong dye-fiber bonding. Copper sulphate also showed enhanced wash (4.0) and rub fastness (4.5), attributed to stable metal-dye complexes. Alum moderately improved all parameters, reaching up to 3.5 in wash and rub fastness. In contrast, sodium carbonate produced the weakest results, particularly in rub fastness (3.0), due to its limited ability to form stable dye-metal linkages. These results underscore the effectiveness of ferrous and copper mordants in improving the durability of natural dyes on cotton.

2. Fastness Analysis of Orange Peel-Dyed Cotton

Fig 1(b) Fastness Analysis of Orange Peel-Dyed Cotton



Senthil Kumar M, Dhinakaran G. Dyeing of cotton fabric using natural dye extracted from orange peel: Effects of mordants on fastness properties. *International Journal of Applied Engineering Research*. 2021;16(5):450–456.

According to Figure 1(b), adapted from Senthil Kumar and Dhinakaran (2020), the fastness performance of orange peel dye on cotton varied with different mordants. Copper sulphate provided the best enhancement, with light fastness at 3.0, wash fastness at 3.5, and rub fastness reaching 4.0, indicating improved dye-fiber interaction. Alum offered limited improvement, achieving 2.5 in light and 3.0 in both wash and rub fastness. Ferrous sulphate showed a decline in performance, especially in wash fastness (3.0), while sodium carbonate showed minimal impact, with light fastness at 2.5 and rub fastness at 3.0. Overall, copper sulphate proved to be the most effective mordant for enhancing the durability of orange peel dye on cotton.

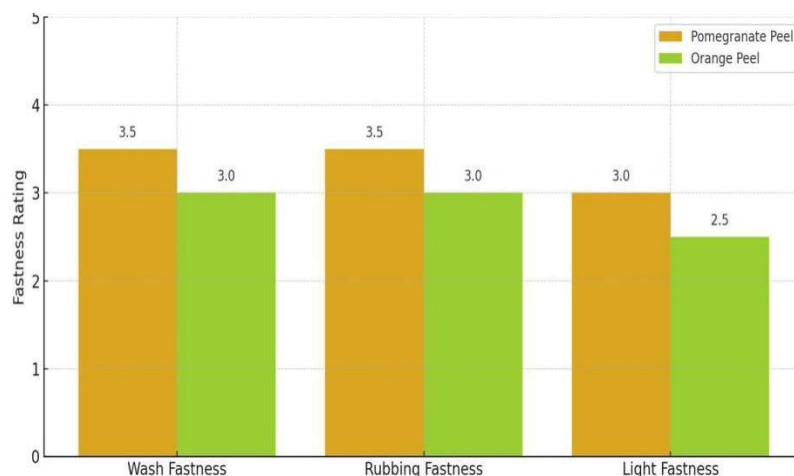
Comparative Evaluation

The results confirm that mordant choice plays a pivotal role in determining the durability of natural dyes on cotton. While ferrous sulfate enhances fastness performance most significantly for pomegranate-based dyes, copper sulfate works better for orange peel dyes. Non-metallic mordants like sodium carbonate tend to yield weaker bonding, leading to lighter and less stable coloration. These findings are in line with earlier studies emphasizing the superior complex-forming capabilities of transition metal mordants.

3. Comparative Fastness Analysis of Mordant on Cotton Dyed with Pomegranate and Orange Peel Extract

1. Fastness Properties of Pomegranate and Orange Peel with Alum

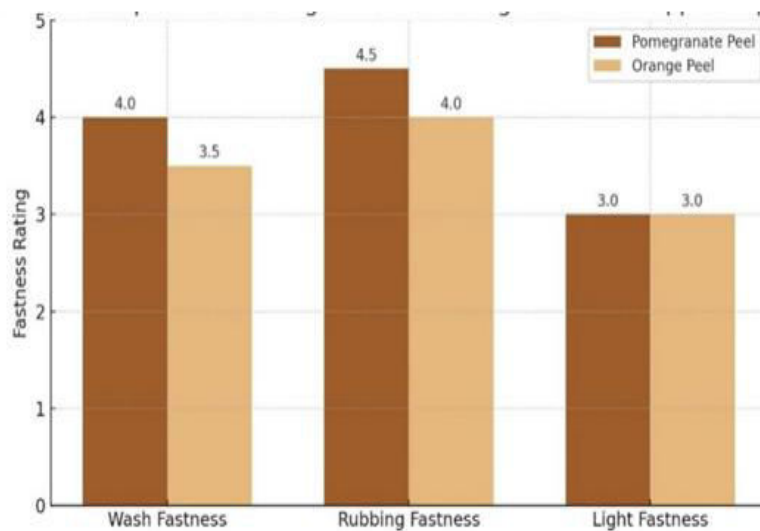
Fig 3 (a): Fastness Properties of Pomegranate and Orange Peel with Alum



Cotton fabrics dyed with pomegranate and orange peel extracts using alum as a mordant displayed moderate overall fastness. Pomegranate peel dye showed slightly superior wash fastness (3.5) compared to orange peel (3.0), likely due to its richer tannin content facilitating better dye-fiber bonding. Rub fastness was comparable, with pomegranate scoring marginally higher at 3.5, indicating decent surface adherence. Light fastness remained modest for both, with pomegranate at 3.0 and orange at 2.5, suggesting alum offers limited UV protection. Color outcomes varied, with pomegranate yielding a mustard yellow and orange peel producing a yellow-green hue, underlining alum's influence on shade development. Given its mild nature and environmental safety, alum offers satisfactory fastness for applications that do not demand high durability.

2. Fastness Properties of Pomegranate and Orange Peel with Copper Sulphate

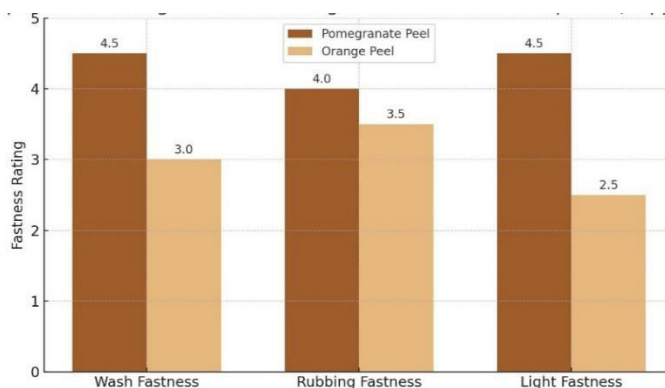
Fig 3(b): Fastness Properties of Pomegranate and Orange Peel with Copper Sulphate



The use of copper sulphate as a mordant revealed stronger fastness performance in pomegranate peel-dyed cotton compared to orange peel. Pomegranate samples showed higher wash fastness (4.0 vs. 3.5) and rub fastness (4.5 vs. 4.0), indicating more robust dye-fiber bonding under both washing and mechanical stress. Light fastness was identical for both dyes (3.0), demonstrating moderate resistance to fading. Visually, pomegranate produced a deeper golden-brown shade, while orange peel yielded a lighter beige-yellow tone, reflecting a higher chromatic intensity in the former. These differences are likely due to the greater polyphenol and tannin content in pomegranate, enhancing its interaction with copper ions during the dyeing process.

3. Fastness Properties of Pomegranate and Orange Peel with Ferrous Sulphate.

Fig 3(c): Fastness Properties of Pomegranate and Orange Peel with Ferrous Sulphate

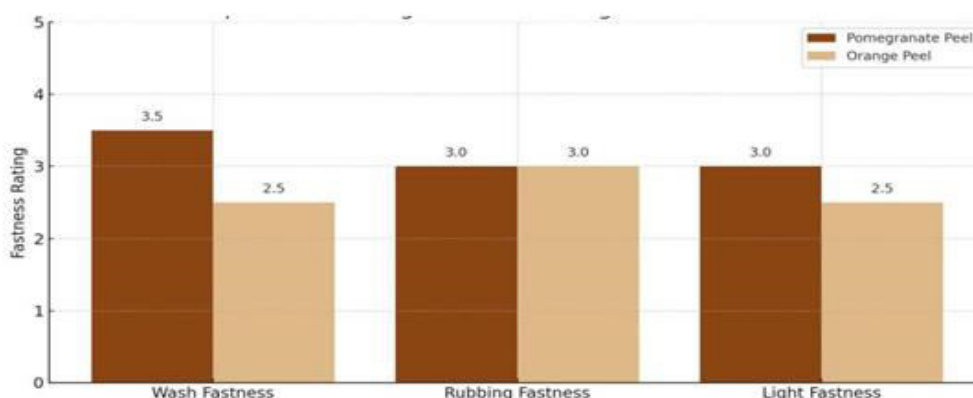


Ferrous sulphate mordanting resulted in significantly better fastness properties for cotton dyed with pomegranate peel compared to orange peel. Pomegranate-dyed fabric exhibited excellent wash fastness (4.5) and strong rub fastness (4.0), while orange peel showed lower values of 3.0 and 3.5, respectively. The disparity in light fastness was most pronounced, with pomegranate scoring 4.5 and orange peel only 2.5, highlighting the latter's susceptibility to photo-degradation. In terms of color, pomegranate produced a rich dark brown to black hue, indicating strong tannin-iron

complexation, whereas orange peel yielded a subdued khaki tone, likely due to its lower tannin content and weaker interaction with ferrous ions.

4. Fastness Properties of Pomegranate and Orange Peel with Sodium Carbonate

Fig 3(d): Fastness Properties of Pomegranate and Orange Peel with Sodium Carbonate



Sodium carbonate, as a non-metallic mordant, yielded moderate dyeing results, with pomegranate peel outperforming orange peel slightly across fastness parameters. Wash fastness was rated at 3.5 for pomegranate and 2.5 for orange, indicating better dye retention in the former. Both dyes showed equal rub fastness (3.0), reflecting average resistance to mechanical friction. Light fastness was also modest, with pomegranate scoring 3.0 and orange 2.5. Color-wise, pomegranate produced a beige-yellow hue, while orange resulted in a pale yellow to cream shade, indicating lower saturation. These outcomes highlight sodium carbonate's limited capacity to enhance dye-fiber bonding compared to metallic mordants like copper and iron.

IV. CONCLUSION

The growing concern over the environmental and health impacts of synthetic dyes has catalyzed significant interest in sustainable alternatives within the textile sector. This research explored the use of pomegranate and orange peels, both agro-waste materials, as natural dye sources for cotton fabrics. By integrating these biowaste-derived colorants with eco-conscious dyeing practices and assessing the role of various mordants, the study aimed to offer a viable pathway toward environmentally responsible textile processing.

The findings confirm that both pomegranate (*Punica granatum*) and orange (*Citrus sinensis*) peels contain bioactive compounds—primarily tannins, flavonoids, and carotenoids—that impart color to cotton fabric when properly extracted and mordanted. Among the mordants tested—alum, copper sulfate, ferrous sulfate, and sodium carbonate—ferrous sulfate consistently facilitated the deepest and most colorfast shades, especially when combined with pomegranate peel extract. This effectiveness is largely attributed to the strong complexation between iron ions and tannin-rich compounds, resulting in intense, dark hues with good fabric adherence.

In contrast, orange peel dyes, while producing aesthetically soft shades, showed limited dye uptake and color intensity, particularly with sodium carbonate. The higher L-values obtained through colorimetric analysis of orange peel-dyed samples reaffirm this trend. However, orange peel still presents potential for use in pastel-toned textiles and applications that prioritize gentle color effects over saturation. The results also highlight the importance of mordant selection, not only for optimizing color strength and uniformity but also for enabling a range of shades from a single dye source. Visual inspection and instrumental color measurements both confirmed that shade variation and durability are highly dependent on the interaction between the bio-pigments and the mordanting agents. The successful application of ferrous sulfate and alum, in particular, suggests that metal-based mordants play a key role in unlocking the full potential of natural dyes for commercial textiles. Beyond their coloring capabilities, both fruit peels offer

additional functional benefits, such as antimicrobial and antioxidant properties, which may enhance the value of the dyed textiles in healthcare and wellness-oriented markets. Pomegranate peel, in particular, shows promise due to its higher concentration of polyphenols, which may contribute to the hygienic performance and longevity of the fabric. From a sustainability perspective, the use of fruit peel waste as dye material supports waste valorization and aligns with circular economy principles. The aqueous extraction method employed is both environmentally benign and practical for small- to medium-scale dyeing operations, requiring minimal technical resources while avoiding hazardous solvents. This approach not only reduces organic waste burdens but also provides a cost-effective, scalable alternative to synthetic dyes.

In conclusion, the study demonstrates the feasibility and benefits of using biowaste-derived dyes, particularly from pomegranate peel, in natural textile coloration. The results affirm that such dyes, when combined with appropriate mordants—especially ferrous sulfate—can produce vibrant and stable shades on cotton fabric. The integration of natural dyes into modern textile applications can help mitigate the environmental load of synthetic chemicals while addressing consumer demand for eco-friendly and ethically produced goods.

Future work could explore enhanced extraction technologies, the use of bio-mordants or plant-based fixatives, and expansion to other waste-derived dye sources. Continued innovation in this field is essential for transitioning the textile industry toward more sustainable and regenerative practices, contributing to long-term ecological health and industry resilience.

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