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Research Article

Dyeing of banana-silk union fabrics with cochineal using different concentrations of bio-mordant

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Abstract: Banana (*Musa* × *paradisiaca* L.) is a lignocellulosic natural fiber that can be processed to produce eco-friendly and biodegradable hybrid fabrics when combined with other fibers. Natural-dyed banana fiber can be utilized in the production of sustainable materials for wearable products, household linens, technical textiles, and apparel. In this study, banana-silk union fabrics, pre-treated with bio-mordant at concentrations of 1%, 2%, 3%, 4%, and 5%, were dyed separately using cochineal insect extract (*Dactylopius coccus* Costa). To assess the dyeability of the banana-silk union fabric, Anatolian black pine cones (*Pinus nigra* subsp. *pallassiana*) were utilized as a bio-mordant, with varying quantities. The CIEL*ab* values of the dyeings were measured and compared. Additionally, the chemical composition of the cochineal extract, pinecone mordant, raw fabric, and selected dyed fabrics was analyzed using Fourier Transform Infrared (FTIR) spectroscopy. The washing, light, and rubbing fastness properties of the dyed banana-silk union fabrics were also evaluated and compared. This study developed a method for weaving union fabric by blending two distinct natural yarns, namely banana and silk, to reduce dependence on a single fiber and promote the utilization of agricultural waste.

1. INTRODUCTION

Natural colorants have been used for centuries to color textiles, food, and other materials (Alegbe & Uthman, 2024). The application and dyeing process of natural dyes is highly efficient, allowing dyeing to be carried out at atmospheric temperature without the need for an external energy source. The entire process is, therefore, economical (Nayab-Ul-Hossain *et al.*, 2023). Compared to synthetic dyes, natural colorants offer several advantages, including their availability, accessibility, and the reduced need for complex chemical extraction processes (Leite *et al.*, 2023). Therefore, the adoption of sustainable natural dyeing techniques in textile production is gaining increasing acceptance. Numerous natural finishing agents and dyes can be utilized to produce UV-protective and antibacterial fabrics. Therefore, natural fibers that have been treated with certain natural finishing agents and dyed with the appropriate natural colorants can provide significant protection against ultraviolet (UV) radiation, microbes, and even mosquito bites (Samanta, 2020). Cochineal insects are one of the best natural sources of red-purple color, and dyestuff is extracted, particularly from the bodies of the female bodies

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from the bodies of female cochineal insects since they grow larger and have purer dye compared to their male counterparts. These insects are typically cultivated on the prickly pear cactus, which serves as their host plant and source of sustenance and they are the source of carminic acid and numerous products, including meals, cosmetics, beverages, medicines, and textiles are colored using carminic acid. (Dapson, 2007). Natural dyes necessitate a mordanting process to ensure the fixation and permanence of color on textile fibers. So, prior to applying natural dyestuffs, it is essential to pretreat the fibers with mordanting agents. This pre-treatment step is crucial as it enhances the bonding between the dye molecules and the fiber, thereby improving colorfastness and overall durability of the dyed textile. (Deveoglu *et al*., 2019). Mordants are categorized into two primary types: metallic mordants and bio-mordants. The use of bio-mordants improves the dyeing process and enhances fastness properties. The textile industry is the largest consumer of water, and comprehensive data on effluent production has also been gathered and extensively documented in the literature. Due to their biodegradability and environmental friendliness, bio-mordants have been proposed by researchers as a safe and effective alternative to metallic salt mordants in textile dyeing. (Hosseinnezhad *et al*., 2021; Rani *et al*., 2020). A range of bio-mordants, such as pomegranate peel, mango peel, tamarind, aloe vera, acacia bark ash, orange peel, amla powder, mustard powder, sodium alginate, lemon peel, and pine cone, have had their dyeing properties extensively studied in the literature. (Shahmoradi Ghaheh *et al*., 2021; Yaqub *et al*., 2020; Yasukawa *et al*., 2017).

The banana (*Musa* × *paradisiaca* L.) is a plant from the Musaceae family and is one of the first domesticated plant species. Historically, the oldest indication of banana stems being utilized as a source of fiber dates to the 13th century. The banana plant is a tall, perennial herb with pseudo-stems formed from leaf sheaths. It can grow to heights of 10–40 feet (3.0–12.2 meters) and is surrounded by 8–12 broad leaves. The leaves may grow up to 2.7 meters long and 2 feet (0.61) broad (Pitimaneeyakul, 2009). Natural fibers, particularly cellulosic-based fibers, have multiple benefits, including low density, high stiffness, and environmental friendliness. Approximately 120–150 million tons of bananas are produced globally each year, yet only 12% of the plant, including the fruit, leaves, and stem, is edible. One hectare of banana cultivation generates approximately 220 tons of waste after the fruit is harvested, accounting for over 60% of the total biomass used in the cultivation process. (Vajpayee *et al*., 2023). More than 1.2 billion tons of stemming bananas are left to rot globally each year. The pseudo stem trunk of a banana plant is discarded as a large agro-waste (Paramasivam *et al*., 2022). Originating in Southeast Asia, the banana is cultivated over an area of 11,154 hectares in Turkey (TÜİK, 2021). The provinces of Antalya and Mersin account for the majority (97.7%) of banana production in Türkiye. The provinces of Antalya and Mersin produce the majority of the bananas (% 97.7) grown in Türkiye (Demirel & Hatirli, 2022; Phromphen, 2023). Banana fiber is predominantly obtained mechanically from the pseudo-stem of the banana plant (Kamel, 2023). As a byproduct, a stem weighing around 37 kg produces roughly 1 kg of high-quality fiber (Shroff *et al*., 2015). Banana fiber consists of the following chemical components: cellulose (50–60%), hemicelluloses (25–30%), lignin (12–18%), pectin (3–5%), fat and wax (3–5%), water-soluble chemicals (2–3%), and ash (1–1.5% of the total fiber (Balakrishnan *et al*., 2019). Banana fibers' low elongation may primarily be caused by their lower microfibrillar angle (11°) and comparatively high crystallinity percentage. Banana stem fibers have tensile properties similar to those of jute and other lignocellulosic fibers (Reddy *et al*., 2015). Textiles, floor mats, and composites are only a few materials made from banana fibers. Lignocellulosic natural fibers, such as those from bananas, can be utilized to produce hybrid or blended fabrics in combination with most other natural fibers (Hassan *et al*., 2022).

The objective of this study was to assess the color properties of cochineal insects (*Dactylopius coccus* Costa) when applied with natural mordants to banana/silk hybrid fabrics. Anatolian black pine (*Pinus nigra* subsp. *pallassiana*) was employed as a bio-mordant to enhance the color characteristics. The color of each fabric was analyzed using CIEL**a**b* values. The fastness characteristics of the dyed samples were evaluated in terms of washing, rubbing, and light resistance. The chemical compositions of the fibers, bio-mordants, and dyestuffs were analyzed using Fourier Transform Infrared (FTIR) spectroscopy.

2. MATERIAL and METHOD

2.1. Material

Cochineal insects were provided by Natural Dyes Company (Istanbul, Türkiye). Anatolian black pine (*Pinus nigra* subsp. *pallassiana*) wood specimens were obtained from the Marmara region (Istanbul, Türkiye). Banana/silk hybrid fabric was obtained from T.C. Alanya Municipality. The weight of the fabric was 200 g/m^2. The warp density per cm is 18, and the weft density per cm is 20. The warp yarn is Ne 30 (silk) and the weft yarn count is Ne 5 (banana).

2.2. Method

2.2.1. *Extraction*

The insects were ground into powder in a mortar before the extraction. The traditional aqua method process was used with a dye concentration set at 5% of over the weight of the fabric (owf) for all dyeings. The liquor-to-fabric ratio was kept to 1:20, lasting 1 hour at boiling temperature. Finally, the temperature of the solution was decreased to 25°C, and it was filtered. The extraction of natural dye is represented in Figure 1.

Figure 1. Extraction of natural dye

2.2.2. *Fabric pre-treatment*

A bleaching process was used to examine the effect of pretreatment applied to the fabrics, and certain samples were pretreated. The bleaching solution comprised sodium hydroxide (3 g/L), soda ash (2 g/L), and a wetting agent (1 g/L) at 70 °C for 60 minutes. Fabric pre-treatment was performed only on samples coded between BF5 and BF10.

2.2.3. *Preparation in powder form of pine cones*

Pine cones were ground into a powder using a vibrating disc mill at 1,000 rpm for 60 seconds. Pine cone powder was added to the dye solution based on the concentration of the bio-mordant required for each dyeing bath. Graining of pine cones for powder form is presented in Figure 2.

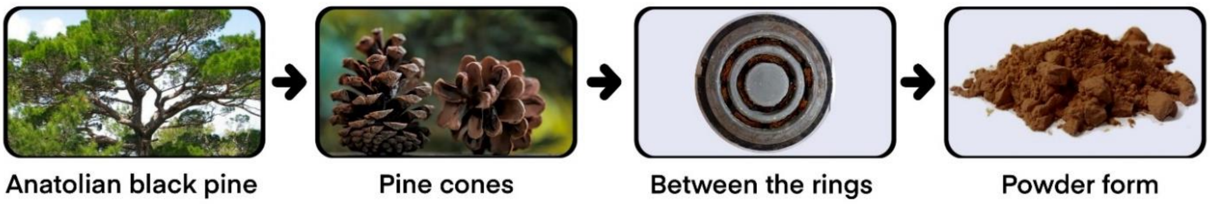
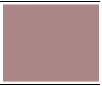
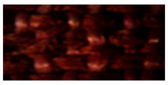
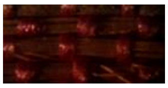


Figure 2. Graining of pine cones for powder form.

2.2.4. *Dyeing procedure*

In this study, banana-silk hybrid fabrics were dyed through a meta-mordant dyeing method with diverse percentages of concentrations. Table 1 summarizes the dyeing procedure.

Table 1. Dyeing procedure.

Dyeing code	Mordant (%)	Pre treatment	Tem. (°C)	Time (min)	Dyeing pH	Shade Microscope	Shade Real
RB	0 RB (RAW)	-	-	-	-		
BF0	0	-					
BF1	1	-					
BF2	2	-					
BF3	3	-					
BF4	4	-					
BF5	5	-	90	120	6-7		
BF6	1	√					
BF7	2	√					
BF8	3	√					
BF9	4	√					
BF10	5	√					

2.2.5. *Fastness properties*

Banana fabrics that had been colored underwent washing, rubbing, and light fastness using ISO standard methods. The colored materials were exposed to xenon arc lamp light for 48 hours (250W). The results of light (ISO 105: B02), rubbing (ISO 105: X12), and washing fastness (ISO 105: C06 -A1S-) tests of dyed fabrics are given in Table 2.

2.2.6. *Color measurement*

The color characteristics were analyzed using a colorimeter. The CIELab values of dyed fabrics are shown in Table 3. The Kubelka-Munk equation for K/S and ΔE*, as shown in Equations 1 and 2.

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

Equation 2: $$\Delta E* = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2}$$

2.2.7. *FTIR analysis*

FT-IR (Fourier Transform Infrared Spectrophotometer) was used to examine dyed and uncolored fabrics in the range of 4000–650 cm^{-1}. FTIR analyses are presented in Figure 4.

3. RESULTS

Producing woven fabric using two different fibers in two directions, warp and weft, is termed union fabric. That is, these woven fabrics combine different types of yarns to create a new product with specialized properties. In union fabrics, the weft yarns are made of one fiber while the warp yarns are made of another (Kaur & Choudhuri, 2020). Banana/silk union (hybrid) woven fabric was weaved by using banana yarn (Ne 5 in the weft) and silk yarn (Ne 30 in the warp). The coloring compounds of cochineal consist primarily of carminic acid and trace amounts of flavokermesic acid. The coloring component (carminic acid) is water-soluble (Karadag, 2023a). The crude natural dye (*Dactylopius coccus* Costa) was extracted from the cochineal insect using the aqueous method. Different bio-mordant concentrations of pinecone were used on union fabrics that had been naturally dyed to evaluate their dyeability. Pine cones contain lignin, cellulose, and tannin (Lee *et al*., 2018). HPLC analysis revealed that pine cones include gallic acid [$C_6H_2(OH)_3CO_2H$], ellagic acid ($C_{14}H_6O_8$), valeric acid ($C_5H_{10}O_2$), as well as minor colorants (Pars, 2024).

Since ancient times, the traditional aqua method has been one of the simplest and oldest methods to extract natural coloring components. In this method, the raw ingredients are first dried, roughly chopped, and frequently ground into a powder before the color components are extracted in boiling water. Following a set amount of time in the boiling process, the substance is cooled to room temperature and filtered. The cochineal insects were ground in a mortar. According to each dyeing recipe, natural coloring extracts of insects were heated up to 100 °C in separate beakers for one hour. Then, the solution temperature was reduced to 25 °C and filtered with filter paper. The meta-mordant dyeing method was used to color the fabrics. The meta-mordant dyeing process was carried out by simultaneously mordanting and dyeing. This technique involves putting the plant or insect having the dyestuff and the mordant material for dyeing into the dyeing bath, which helps to save both cost and energy. The fabrics were immersed in a dye bath solution comprising both bio-mordant that was put into the dye solution and insect dye (prepared in the aqua method) at a liquor ratio (L/R) of 1:50 (at 90 °C for 120 min). All fabrics were dyed with 5% cochineal (owf) with different concentrations of pinecone (1 %, 2%, 3%, 4%, and 5%) in separate beakers. The dyed materials were then rinsed and dried at room temperature. The dyeing scheme is presented in Figure 3. The dyeing was done per the Natural Organic Dye Standard (NODS). By nature, hazardous substances, heavy metals, carcinogenic dyes, toxic dyes, pesticides, and synthetic dyes are excluded from the NODS. Therefore, brands and the textile industry can accomplish more by creating materials that abide by the NODS while also promoting sustainability and eco-friendly dyeing (Karadag, 2023b). The procedure of dyeing, microscope shades, and real shades are given in Table 1.

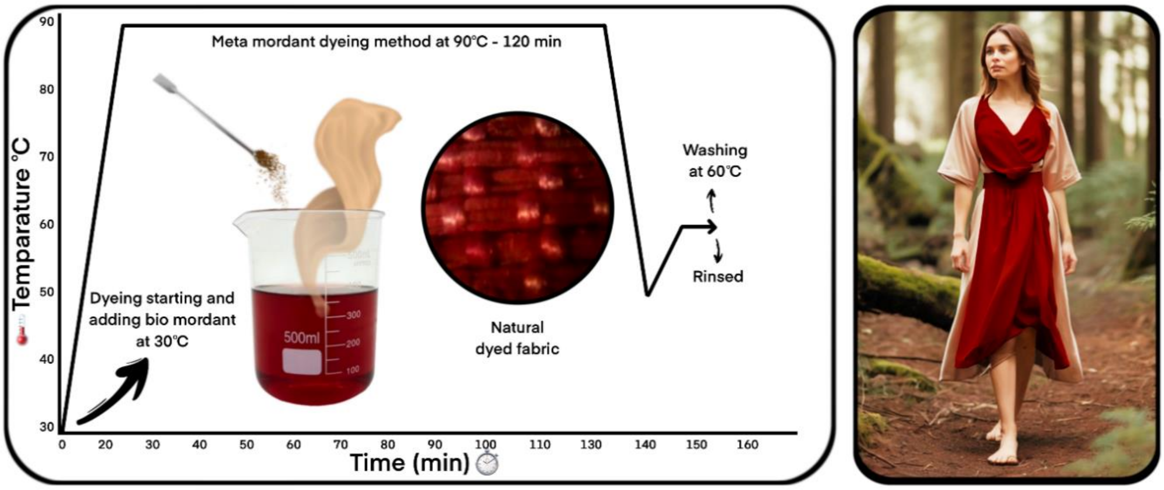


Figure 3. Dyeing scheme.

The lightfastness of all the fabrics was found to be varyingly low, which is typical of natural dyeing in cellulosic-based materials. The results of washing fastness tests on dyed fabrics were good. All of the dyed fabrics exhibit good rubbing fastness ratings of 4-5 in dry conditions, with the lowest ratings being 3-4 in wet conditions. Table 2 provides the results of the light, rubbing, and washing fastness tests for the dyed fabrics.

Table 2. The results of light, rubbing, and washing fastness tests of dyed fabrics.

Code	Light	Rubbing		Washing-Staining					
		Dry	Wet	Acetate	Cotton	Nylon	Polyester	Avyrlic	Wool
BF0	-	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF1	2-3	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF2	2-3	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF3	2-3	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF4	2-3	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF5	3	5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF6	2-3	4-5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF7	2-3	5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF8	2-3	5	3-4	4-5	4-5	4-5	4-5	4-5	4-5
BF9	3	5	4	4-5	4-5	4-5	4-5	4-5	4-5
BF10	3	5	4	5	5	5	5	5	5

The chemical components in the cochineal, pinecone, raw, and selected dyed fabrics (BF5 and BF10) were detected using FTIR analysis. The bands between 1440 cm^{-1} to 1000 cm^{-1} can be related to carbohydrate functional groups. The aromatic ring at 1513 cm^{-1} and the aromatic methoxyl at 1239 cm^{-1} were bands related to lignin (Pereira *et al.*, 2014). The –OH stretching was identified as the cause of the distinctive broad peaks around 3277 cm^{-1}, which correspond to the stretching vibrations of cellulose, hemicellulose, and absorbed moisture. The intensity of the - OH stretching peaks increased after dyeing. It was also determined that the peaks at 2918 to 2919 cm-1 were caused by the C-H stretching vibration from the -CH_2 group of cellulose and hemicellulose (Oyewo *et al.*, 2023). The molecular vibrations at 1543 and 1242 cm^{-1} may be attributed to the presence of C–C and C–OH groups in the cochineal molecule (Kumar *et al.*, 2016). The peak characteristic of cochineal around 2850 cm^{-1} was attributed to the asymmetric stretching vibration of the C–H bond in alkanes. These bonds of cochineal were also determined in the selected samples (BF5 and BF10) at 2853 cm^{-1} and the presence of hydroxyl –OH and carbonyl -C=O groups in the structure of pinecones may indicate an improvement in the color properties of dyed fabrics. IR spectra revealed evidence of the interaction between the dye, bio-mordant, and fiber, indicating the formation of a complex. The results of the FTIR analysis are presented in Figure 4.

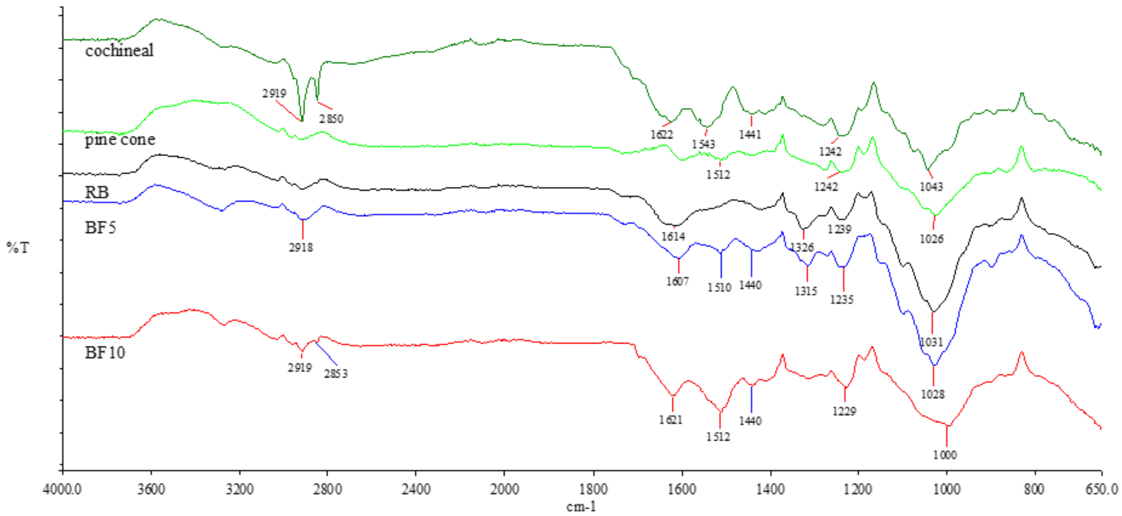


Figure 4. The analysis results carried out by FTIR.

The color of each dyed fabric was investigated based on the CIELAB (L*, a*, and b*) values. Before dyeing to increase hydrophilicity, a fabric pretreatment process was carried out to remove oil, wax, and natural impurities from the banana. For the pretreatment process, only fabrics coded between BF5 and BF10 were bleached with sodium hydroxide (NaOH) at a quantity of 3 g/L with 2 g/L soda ash and 1 g/L wetting agent running at 70 °C for 60 min at a 1:50 liquor ratio. Thus, the effect of the pre-treatment applied to the material on the fabric was examined. The CIEL*a*b* values of dyed fabrics are given in Table 3. The measurements were taken at 22°C (65 ±2% relative humidity), D65 daylight, with a 10° standard observer, and the raw fabric was used as the standard. Three values (L*, a*, and b*) are used to represent color in the CIE-LAB color space. From black to white, the perceptual lightness is expressed by L* (brightness) [between 0-100]. Red, green, blue, and yellow are the four hues that a* and b* refer to. With a value range of a* representing the green-red opponent colors and b* representing the blue-yellow opponent colors. The BF10-coded fabric had the highest color yield of all the colored fabrics (K/S = 10.31) at the wavelength of maximum absorption. As shown in Table 3, the sequence of color intensity (K/S value) of different dyed fabrics is BF10 > BF9 > BF8 > BF7 > BF6 for pretreated fabrics. This indicates that the mordant with 5% pinecone produced the highest color yield. The color difference (ΔE*) values of the dyed fabrics were found in the range of 4.19 to 10.31 when the sample "RB" was used as a standard (the highest ΔE* value was found to be 10.39 for the sample BF10 and the lowest color difference was 16.16 for the sample BF0). Banana fiber contains cellulose, which is the highest among the fibers obtained from other parts of the banana plant, hemicellulose, lignin, wax, ash, and moisture (Karuppuchamy *et al*., 2024). Thus, fabric pre-treatment was found to enhance color strength, and before the dying and mordanting processes, cellulosic fabrics may undergo pre-treatment.

The novel method of bio-mordant utilized in this study is gaining recognition for its ability to produce new shades with exceptional fastness qualities. Varied colors were produced by using different ratios of bio-mordants. The color strength was affected by the mordant concentration (ranging from 1% to 5%).

Table 3. The CIELab values of dyed fabrics.

Code	*L**	*a**	*b**	*C**	*h°*	K/S	ΔE*
RB	74.07	5.06	15.92	16.71	72.39	-	-
BF0	61.68	11.34	7.66	13.69	34.05	4.19	16.16
BF1	59.42	14.06	5.32	15.03	20.73	4.20	20.19
BF2	57.54	13.02	6.15	14.40	25.28	5.00	20.79
BF3	57.85	13.37	6.14	14.71	24.65	5.79	20.69
BF4	49.58	13.51	6.82	15.13	26.80	7.07	27.46
BF5	48.06	13.70	5.84	14.90	23.08	7.45	29.20
BF6	50.35	15.41	4.51	16.05	16.31	6.50	28.28
BF7	48.06	13.70	5.84	14.90	23.08	6.63	30.79
BF8	47.01	14.95	3.32	15.31	12.51	7.03	31.44
BF9	41.93	14.65	4.10	15.21	15.66	9.45	35.56
BF10	37.03	14.56	3.86	15.06	14.85	10.31	39.10

Annually, enormous amounts of pinecones, a common agricultural waste, are produced and utilized in a variety of industries. Numerous research studies on banana fiber have spurred investigations into its novel uses in the textile sector, including value addition and enhancement of fabric qualities. Furthermore, Environmental concerns, which are driving the demand for natural materials as alternatives to synthetic reinforcements in composite products, suggest that the use of banana fiber as reinforcement in polymers is likely to increase in future technical textile applications (Makinde-Isola *et al*., 2024). The study developed a method of weaving the union fabric by combining two various quality natural yarns like banana and silk to reduce the dependence on a single fiber and to promote the use of agricultural waste.

4. CONCLUSION

Banana/silk union fabrics bio-mordanted at rates of 1%, 2%, 3%, 4%, and 5% were separately dyed with cochineal (*Dactylopius coccus*). Various ratios of Anatolian black pine (*Pinus nigra* subsp. *pallassiana*) have been used effectively as bio-mordants. Banana fibers can be dyed with natural colors to a significant extent, which will help mitigate pollution and address ecological imbalances, contributing positively to environmental conservation. The principal objective of this current study was to evaluate the effects of bio-mordants including natural dye extract on banana fiber in terms of color measurement and color fastness. The hydrophilicity of banana-silk hybrid fabrics was improved by diminishing lignin, fats, and wax contents with fabric pre-treatment. It was determined that the color strength was influenced by the pretreatment and bio-mordant concentration used. Bio-mordants enhance the bonding of natural dyes to the fiber and may be used as biodegradable versus metallic mordants. The coloristic properties of the dyed fabrics were enhanced due to the high concentration of bio-mordant, which utilized pinecones to form complexes with carminic acid and the fiber. A lingo-cellulosic natural fiber, bananas can be treated to combine with other fibers to develop a hybrid fabric that is both biodegradable and ecologically safe. Banana fiber that has been naturally dyed may be utilized to create eco-friendly materials for clothing, technical textiles, wearable technology, and home linens.

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Declaration of Conflicting Interests and Ethics

The authors declare no conflict of interest. This research study complies with research and publishing ethics. The scientific and legal responsibility for manuscripts published in IJSM belongs to the authors.

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