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APPLICATION OF DBD PLASMA AS PRETREATMENT OF COTTON FABRIC TO ENHANCE THE AFFINITY OF NATURAL DYE EXTRACTED FROM OIL PALM EMPTY FRUIT BUNCH WASTE WITH IMAGE PROCESSING EVALUATION

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ABSTRACT

The use of oil palm empty fruit bunch (EFB) waste as a natural dye source was investigated via a novel plasma pretreatment approach. The dye extract was obtained by boiling the EFB in distilled water at 100 °C for one hour. Cotton fabrics were dyed using the exhaust method at 50 °C and pH 4 for 90 minutes, with some samples additionally treated with dielectric barrier discharge (DBD) plasma for 30 seconds. Alum mordanting was also applied as a comparison. Color analysis was conducted using an image-processing method based on RGB values, which revealed that both plasma treatment and mordanting individually increased color intensity relative to the control. The combination of plasma pretreatment and mordanting produced the highest color difference, with a distance value of 0.384, indicating a synergistic effect between plasma-induced fiber surface modification and crosslinking facilitated by the mordant. These findings highlight that integrating DBD plasma technology with natural dyeing, as evaluated using image processing, offers a promising pathway to enhance color uptake while promoting more sustainable and eco-friendly textile dyeing processes.

ABSTRAK

Pemanfaatan limbah tandan kelapa sawit sebagai sumber zat warna alami dieksplorasi dengan pendekatan baru berupa pretreatment plasma. Ekstrak pewarna diperoleh melalui perebusan tandan kelapa sawit dalam air suling pada suhu 100 °C selama satu jam. Proses pencelupan dilakukan pada kain kapas dengan metode exhaust pada 50 °C, pH 4, selama 90 menit, dengan variasi sampel yang diberi perlakuan plasma dielectric barrier discharge (DBD) selama 30 detik maupun tanpa plasma. Proses mordanting menggunakan tawas juga dijadikan pembanding. Analisis warna dilakukan menggunakan metode image processing berbasis nilai RGB, yang menunjukkan bahwa plasma maupun mordanting masing-masing berkontribusi meningkatkan intensitas warna dibanding kontrol. Kombinasi keduanya menghasilkan perbedaan warna terbesar dengan nilai distance 0,384, menandakan adanya efek sinergis antara modifikasi permukaan serat oleh plasma dengan pembentukan ikatan silang akibat mordant. Temuan ini menegaskan bahwa integrasi teknologi plasma DBD dengan zat warna alam, yang dievaluasi melalui image processing, dapat mendukung pengembangan proses pewarnaan tekstil yang lebih ramah lingkungan dan berkelanjutan.

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INTRODUCTION

The textile industry is among the manufacturing sectors with the highest consumption of water, energy, and chemicals, particularly during the dyeing and finishing stages of fabric production (Kant, 2012). Conventional dyeing processes using synthetic dyes have become a global concern due to their significant contribution to environmental pollution. Synthetic dyes generally contain aromatic compounds, heavy metals, and other hazardous chemicals that are persistent and difficult to decompose in aquatic environments (Ardila-Leal et al, 2021). Liquid waste generated from dyeing activities has been reported to be a significant source of water-quality degradation, causing ecotoxicological problems and threatening the health of humans and aquatic organisms (Allègre et al, 2006).

In the context of sustainability, natural dyes are again gaining attention as an environmentally friendly alternative. Natural dyes are highly biodegradable, low-toxicity, and derived from renewable sources (Saxena & Raja, 2014). Despite its environmental advantages, the use of natural dyes in the textile industry remains hindered by technical challenges. Common problems include low color intensity, limited absorption, and inadequate fastness to washing and rubbing (Shariful Islam et al, 2020). To improve the performance of natural dyes, a common approach is mordanting, which involves using metal salts such as alum, copper, or iron to strengthen the bond between dye molecules and textile fibers. However, the use of metal-based mordants can create new environmental problems due to their toxicity and difficulty of decomposition when used excessively (İşmal & Yildirim, 2018).

On the other hand, Indonesia offers significant potential for supplying natural dye raw materials derived from agricultural biomass waste. As a major palm oil producer, Indonesia recorded a plantation area of 15.93 million hectares in 2023, with total palm oil production of 47.08 million tons, a 0.55% increase from the previous year (Badan Pusat Statistik, 2024). This production generates large amounts of biomass waste, one of which is empty fruit bunches (oil palm bunches), which account for 20–22% of the total fresh fruit bunch mass (Erivianto & Dani, 2024). Currently, most oil palm bunch waste is used as mulch or even left to rot. Therefore, utilizing it as a source of natural dyes could be a value-added solution.

Previous research has shown that oil palm bunches contain natural pigments such as tannins and flavonoids. Tannins are known to produce brownish-yellow colors, while flavonoids can produce a spectrum of yellow, red, and even blue colors depending on their chemical structure and pH conditions (Zhang et al, 2022; Zuber et al., 2020). These compounds have the potential to be used as natural dyes for textiles. However, like natural dyes in general, the main challenges faced are the limited affinity of the dye for cotton fibers and its color stability.

With the development of environmentally friendly technologies, cold plasma has emerged as a promising alternative for fiber surface modification. One widely studied method is Dielectric Barrier Discharge (DBD) plasma. DBD plasma can generate active radicals, ozone, and intense electric fields that physically and chemically modify fiber surfaces (Wijayono et al., 2025; Putra et al, 2020; Wijayono et al, 2019). These modifications include increased surface energy, coarsening of the microscopic topography, and the formation of new oxygen functional groups such as –OH, –COOH, and –C=O, which enhance the fiber's hydrophilicity (Mather, 2009; Peran & Ražić, 2020). Thus, DBD plasma treatment has the potential to increase the absorption and affinity of cotton fibers for natural dyes without the need for additional chemicals, making it more environmentally friendly than conventional mordanting processes.

Building on this background, this study aims to examine the use of DBD plasma pretreatment of cotton fabric to enhance the affinity of natural dyes extracted from oil palm bunch waste. The dyeing process was carried out using the exhaust method, and the dyeing results were evaluated using RGB-based image processing to obtain objective quantitative data. It is hoped that the results of this study will contribute to the integration of DBD plasma technology with natural dyes, thereby supporting the development of more environmentally friendly, efficient, and sustainable textile dyeing processes.

METHODS

This research method was designed experimentally by utilizing primary data obtained directly from sample testing results. The main substrate used was 100% ready-for-dye (RFD) cotton woven fabric with a grammage of 120 g/m^2, plain weave construction, 60 ends per cm and 56 picks per cm, obtained from the AK-Tekstil Solo Weaving Workshop, Surakarta. The dye was obtained from oil palm bunch waste extract, with the addition of acetic acid as a pH regulator and alum at a concentration of 6 g/L as a mordant. Distilled water was used throughout the extraction and dyeing processes. The equipment used included a glass dyeing vessel, a temperature-controlled hot plate, an analytical balance, a Brother DCP-T700W scanner connected to a computer, and AW Digital Image Processing software for color image analysis. Dye extraction was carried out by boiling oil palm bunch waste in distilled water at 100°C with a material-to-solvent ratio of 1:25 for 60 minutes (Rossi et al., 2017). The extraction process was repeated twice under the same conditions to obtain optimal extraction results. The resulting filtrate was then used as a dyeing solution. The dyeing process was carried out using the exhaust method using a solution ratio of 1:15, at 50°C for 90 minutes, with conditions maintained at pH 4 using acetic acid.

In addition to dyeing and mordanting, this study also involved plasma treatment. Plasma was generated through a Dielectric Barrier Discharge (DBD) reactor with glass-coated metal plate electrodes as the dielectric. The reactor operated using a high-frequency AC power source of 25 kHz at a voltage of 3 kV, with a distance between the electrodes of 3 mm. The plasma treatment was applied to the cotton fabric surface for 30 seconds under ambient air conditions, ensuring that the fabric temperature did not experience significant heating during the treatment process.

Based on these treatment combinations, four process variations were obtained: dyeing without plasma and without mordanting, dyeing without plasma and mordanting, dyeing with plasma without mordanting, and dyeing with plasma and mordanting. The mordanting process was carried out using a post-mordanting approach. At this stage, the dyed fabric was immersed in 150 mL of mordant solution at 50°C for 60 minutes. After the process was complete, the fabric was washed with running water until clean and then dried at room temperature.

To evaluate changes in fabric surface properties due to the plasma pre-treatment, a water absorption test was conducted using the drop test method. The test was performed by dropping a drop of distilled water from a height of 1 cm using a pipette onto the surface of a flat-laid fabric sample. The time required for the water drop to be fully absorbed was recorded using a stopwatch. Each sample was tested at three different points, and the results were expressed as the average absorption time. This test was used to assess the increase in fabric hydrophilicity after plasma treatment and its relationship to natural dye uptake.

Fabric images were acquired using a Brother DCP-T700W scanner with a resolution of 1200 dpi, PNG file format (uncompressed), and brightness and contrast parameters kept at 0% (default). All samples were scanned under identical conditions without additional digital modification or correction by the scanner's built-in software. This approach was chosen to maintain the accuracy of the RGB values for analysis through image processing.

All treated samples were then analyzed using image processing techniques. The analysis was performed by comparing images of control fabric (untreated) with images of fabric that had undergone plasma treatment or mordanting. The main parameter analyzed was the RGB (Red, Green, and Blue) values of each fabric image. The use of this image processing method was proposed due to limited access to a spectrophotometer in the laboratory. However, measuring the RGB values of the fabric images still provides an adequate quantitative description to evaluate the differences in the affinity levels of natural dyes from oil palm bunch waste to cotton fabric, especially in the combination of DBD plasma and post-mordanting treatments.

RESULT AND DISCUSSION

This study investigated the use of oil palm bunch waste extract as a natural dye for 100% RFD cotton woven fabric. Extraction was carried out by soaking in distilled water at 100°C for one hour, repeated twice to obtain the optimal extract. Active compounds such as tannins and flavonoids dissolved into the solution, producing a dark brown color (as shown in Figure 1). The extract solution had a pH of approximately 8, then adjusted to pH 4 using acetic acid before dyeing. Figure 1(a) shows the oil palm bunch extraction solution obtained in this study.

(a) (b)

Figure 1. Results of oil palm bunch extraction; (a) oil palm bunch extract solution, (b) distilled water

Dyeing cotton fabric with oil palm bunch extract involves an adsorption reaction, where hydrogen bonds form between the hydroxyl (-OH) groups of tannin in oil palm bunch extract and the hydroxyl (-OH) groups in the cellulose of cotton fibers (Nuramdhani et al, 2024). This causes the more acidic the pH of the dyeing solution, the higher the affinity of the dye for the fiber because the acidic conditions increase the interaction between the dye molecules and the fiber. The reaction between cotton fibers and tannin from oil palm bunch extract can be seen in Figure 2.

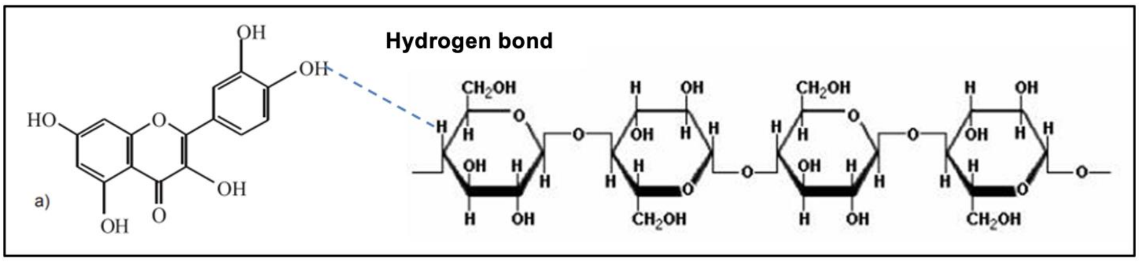

Figure 2. Reaction scheme of cotton fiber with tannin extracted from oil palm bunches

Fabric dyeing was carried out using various plasma and mordant treatments. Visually, fabric treated with plasma and mordant showed a more intense color compared to other treatments, while fabric without plasma and without mordant had the lightest color. This indicates a synergistic effect between plasma and mordant in increasing the affinity of the dye to the fiber. Figure 3 shows the appearance of the dyed fabric resulting from various plasma and mordant treatments.

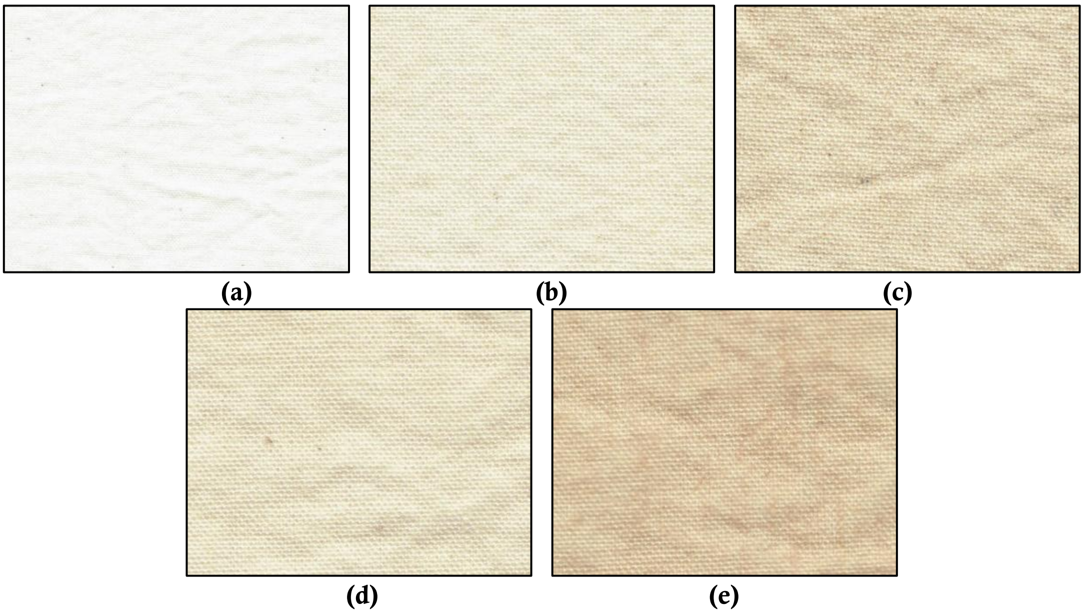

Figure 3. Comparison of the results of dyeing cotton fabric using the exhaust method using oil palm bunch waste extract; (a) blank, (b) without plasma and without mordant; (c) given mordant and without plasma; (d) given plasma and without mordant; (e) given plasma and mordant

To evaluate the change in the fabric surface hydrophilicity induced by plasma, a drop test was conducted. The results showed that the fabric without plasma required up to 31 seconds to absorb water droplets, while the fabric that had been treated with plasma exposure (for 30 seconds) only required 1 second of absorption time (the results can be seen in Table 1). This increase in absorption indicates that plasma can add polar groups (-OH, -COOH) and increase surface roughness, thus facilitating the penetration of the dye solution into the fiber.

Table 1. Water droplet absorption time on cotton cloth

Treatment	Absorption time (seconds)
No plasma treatment (blank)	31
Plasma for 5 seconds	30
Plasma for 15 seconds	19
Plasma for 30 seconds	1
Plasma for 45 seconds	1
Plasma for 90 seconds	1

Color analysis of the fabric was conducted using a digital image-processing approach, namely by calculating the average intensity in each red (R), green (G), and blue (B) color channel of the scanned image. Table 2 shows the results of the color analysis of the dyed fabric obtained in this study. The intensity values were then normalized to the 0–1 scale for easier comparison. Undyed fabric was used as a reference. Next, the color difference between the blank and dyed fabrics was calculated using the Euclidean distance in the RGB color space. This digital image-based analysis approach is consistent with previous studies that utilized image processing techniques to evaluate various textile parameters, including stitch per inch measurements (Wijayono & Putra, 2018), woven fabric density (Wijayono et al., 2019), fabric homogeneity (Putra et al., 2020), and fabric cover factor (Wijayono & Murti, 2024).

$$D = \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2} \quad \ldots 1)$$

Table 2. Average RGB channel values and color difference (D) values of digital images of dyed fabric samples.

Sample Type	Normalized RGB (0-1)			Distance
	R	G	B	
Blank	0.967 ± 0.025	0.969 ± 0.024	0.956 ± 0.034	
No Plasma No Mordant	0.928 ± 0.032	0.910 ± 0.032	0.827 ± 0.036	0.147
No Plasma + Mordant	0.882 ± 0.049	0.830 ± 0.051	0.715 ± 0.053	0.291
Plasma + No Mordant	0.908 ± 0.055	0.879 ± 0.058	0.776 ± 0.065	0.210
Plasma + Mordant	0.857 ± 0.063	0.775 ± 0.068	0.643 ± 0.067	0.384

Digital image analysis in the RGB channel shows that the control fabric has an average value of R = 0.967, G = 0.969, and B = 0.956. The Euclidean distance value to the blank (D) increases after dyeing, in the following order: No Plasma No Mordant (D = 0.147) < Plasma + No Mordant (D = 0.210) < No Plasma + Mordant (D = 0.291) < Plasma + Mordant (D = 0.384). These data indicate that plasma increases dye penetration, and the effect is stronger when combined with a mordant.

Based on the Euclidean distance (D) values in Table 1, the combination of plasma and mordant treatments yields the highest D value (0.384), compared with the other treatments. This indicates that fabric dyed with plasma and post-mordant treatments had the highest color intensity, while fabric without plasma and without mordant showed the lowest color difference (D = 0.147). In the post-mordant treatment, the dye has the opportunity to penetrate maximally into the fiber before the mordant is added, thus strengthening the bond between the dye molecules and the fiber. Al^{3+} ions from alum act as coordination bridges, forming cross-links between the tannin, alum, and cellulose in the cotton fiber. These cross-links are stabilized through a combination of hydrogen bonds and covalent coordination bonds, resulting in fabric with more intense color and improved colorfastness. Conversely, treatments without plasma and without mordant showed lower dye affinity due to limited interaction between the dye molecules and the fiber, resulting in lower color intensity.

The role of DBD plasma can be explained by the increased number of polar groups on the fiber surface and morphological changes that increase the contact area and surface roughness, allowing the dye solution to diffuse more rapidly. The –OH groups in tannin remain hydrogen-bonded to cellulose, while the Al^{3+} ions from alum act as coordination bridges, forming stable cross-links between tannin and fiber, enhancing color intensity and fastness. The combination of plasma and mordant exhibits a synergistic effect, increasing dye affinity and dyeing efficiency.

Color homogeneity analysis, based on the standard deviation of the RGB channels, showed that plasma treatment produced a less uniform color distribution than the fabric without plasma treatment. The highest SD value was observed for the plasma + mordant combination, indicating color variation in the dyeing results. Although increased hydrophilicity and surface morphology modification due to plasma exposure facilitated dye diffusion, the plasma exposure may not have been uniform across the fabric surface.

Overall, DBD plasma treatment significantly increased fabric hydrophilicity, dye affinity, and color intensity. This effect synergizes with Al^{3+} ions from alum, making the plasma-post-mordanting combination the most effective approach for dyeing cotton fabric with oil palm waste extract.

CONCLUSION

This study proves that pretreatment of cotton fabric using Dielectric Barrier Discharge (DBD) plasma significantly increases the fabric's affinity for natural dyes extracted from oil palm bunch waste. DBD plasma treatment is able to drastically increase the surface hydrophilicity of cotton fibers, as indicated by a decrease in the water droplet absorption time from 31 seconds on untreated fabric to only 1 second after 30 seconds of plasma treatment. This modification increases the number of polar groups (–OH, –COOH) and the roughness of the microscopic topography, thereby enabling the dye solution to penetrate the fiber more efficiently. In addition, the use of alum as a post-mordant facilitates cross-linking between tannin molecules and cotton fibers via coordination with Al^{3+} ions, thereby strengthening the fabric's color intensity and fastness. The combination of plasma and post-mordanting treatments exhibits the optimal synergistic effect, producing the highest color difference ($\Delta E = 0.384$) compared with single treatments or controls, confirming that plasma facilitates dye penetration. At the same time, the mordant strengthens the bond and color stability. RGB value-based image analysis proved effective for quantitative evaluation of color intensity and color difference, offering a practical alternative when access to a spectrophotometer is limited. However, the color distribution in plasma-treated fabrics tended to be less homogeneous, likely due to variations in plasma exposure, which is an important consideration for industrial-scale applications. Overall, integrating DBD plasma technology with natural dyes derived from oil palm bunch waste offers a more environmentally friendly, efficient, and sustainable approach to textile dyeing, while reducing reliance on harmful synthetic chemicals and supporting greener textile dyeing innovations.

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