Enhancing the Sustainability of Kenaf-Cotton Blends: The Role of Pre-treatment in Optimized Solubilized Vat Dyeing

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Abstract The use of non-conventional natural fibers in textiles requires appropriate processing to achieve acceptable dyeing performance. Kenaf fiber offers environmental benefits but presents dyeing challenges due to its complex fiber structure. This study aims to analyze the impact of pre-treatment on the dyeing characteristics of solubilized vat dyes applied to handloom-woven kenaf and handspun cotton fabrics. Four pre-treatment conditions were examined: untreated, scouring, bleaching, and combined scouring–bleaching. The fabrics were dyed under controlled conditions and evaluated through fabric characterization, visual color assessment, and color fastness tests to washing, rubbing, and perspiration. The results show that pre-treatment has a significant effect on dye uptake, color uniformity, and durability. The combined scouring–bleaching treatment produces the most uniform and intense color and achieves excellent color fastness performance. These improvements are associated with enhanced fiber cleanliness and improved accessibility of the fiber structure for dye fixation. This study demonstrates that pre-treatment is a key factor in optimizing the dyeing performance of kenaf–cotton blended fabrics and provides practical insights for the development of sustainable and value-added textile products.

1 Introduction

The textile and fashion industry is one of the major contributors to the global economy. However, it is also recognized as a significant source of environmental impact, particularly due to its heavy reliance on synthetic fibers and the extensive use of hazardous chemicals in dyeing processes [1]. This situation has intensified research interest in the development of sustainable and environmentally friendly textile raw materials. Within this context, the utilization of non-conventional natural fibers has become an important focus in sustainable textile research [2].

Kenaf (*Hibiscus cannabinus*) has been identified as a promising natural fiber owing to its favorable ecological characteristics, including rapid growth, biodegradability, and sufficient fiber strength for textile applications [3]. Previous studies have indicated that

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kenaf has considerable potential as an alternative textile raw material when processed using appropriate technological approaches. Beyond conventional textile applications, kenaf fibers have also been widely explored in other advanced material systems. Owen [4] demonstrated the use of kenaf fibers as reinforcement in recycled PET composites to improve mechanical performance, while Kamarudin et al. [5] reported their effectiveness in PLA-based bio composites using vegetable oil–based plasticizers. Despite these advances, the application of kenaf fibers in textile dyeing remains challenging due to their complex lignocellulosic structure and limited dye fiber interactions.

Besides of that kenaf has considerable potential as an alternative textile raw material when processed using appropriate technological approaches. Nevertheless, the application of kenaf in textile products remains technically challenging, particularly with respect to dyeing performance.

Although numerous studies have reported the sustainability potential of kenaf fibers, most existing research has primarily focused on fiber characterization, basic chemical modification, or non-textile applications such as composites and technical materials [6]. Studies specifically addressing the dyeing performance of kenaf in the form of finished textile structures, especially woven fabrics, remain limited. Furthermore, available dyeing studies are largely conducted on kenaf fibers or yarns alone, which do not fully represent dyeing behavior in blended fabrics under realistic production conditions [7].

The role of pre-treatment in improving dye uptake has been widely studied for conventional machine-woven cotton fabrics. However, due to the higher lignin content and rigid fiber structure of kenaf, its response to pre-treatment cannot be directly equated with that of cotton [8]. To date, limited understanding exists regarding how different pre-treatment methods affect fiber accessibility, kenaf–cotton interactions, and dyeing performance in blended fabrics.

Moreover, although Indigosol dyes are commonly used for cellulosic fibers, most studies focus on industrial cotton or machine-woven textiles. Research on solubilized vat dyeing of handloom-woven fabrics made from kenaf and handspun cotton remains scarce, despite the unique fabric structures produced by traditional spinning and weaving processes that can influence dye diffusion, fixation, and color uniformity.

Based on this literature review, a research gap is identified in the lack of studies examining the integrated relationship between pre-treatment type, structural characteristics of handloom-woven handspun kenaf–cotton fabrics, and the dyeing performance of solubilized vat dyes. Previous studies have not systematically investigated how pre-treatment strategies and fabric structure influence color uptake, dyeing uniformity, and color fastness in kenaf–cotton blended textiles. Therefore, this study aims to clarify the role of pre-treatment in optimizing the dyeing performance of kenaf–cotton fabrics within the context of sustainable textile craftsmanship.

The objective of this research is to analyze the impact of pre-treatment on the dyeing characteristics of Indigosol dyes applied to handloom-woven kenaf/handspun cotton fabrics. The findings are expected to contribute scientifically to the development of non-conventional natural fiber textiles and to offer practical, application-oriented solutions for artisans, small and medium-sized enterprises, and the broader advancement of value-added sustainable textiles.

2 Method

2.1 Characterization of handloom-woven handspun kenaf–cotton fabrics

The handloom-woven handspun kenaf–cotton fabrics were characterized to determine their basic construction and physical properties prior to pre-treatment and dyeing. Fabric construction analysis included measurements of warp and weft density (ends per inch and picks per inch), weave structure, fabric weight expressed as grams per square meter (GSM), yarn count, and fabric/yarn shrinkage. All measurements were conducted on untreated fabrics to establish baseline characteristics that could influence dye absorption and colorfastness performance.

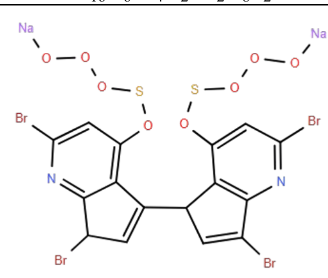
2.2 Pre-treatment procedure of handloom-woven handspun kenaf–cotton fabrics

Four pre-treatment conditions were applied to the fabrics, namely untreated (control), scouring, bleaching, and combined scouring–bleaching. Scouring was performed using an alkaline solution containing sodium hydroxide (NaOH 38°Bé), sodium carbonate (Na_2CO_3), and a wetting agent (Teepol) to remove natural impurities such as oils, waxes, and residual lignin [9]. Bleaching was carried out using hydrogen peroxide (H_2O_2) in the presence of sodium silicate (waterglass), sodium hydroxide (NaOH 38°Bé), and teepol to improve fabric whiteness and fiber accessibility [10]. For the combined scouring–bleaching treatment, the fabrics were subjected to a sequential or integrated process using hydrogen peroxide, waterglass, sodium hydroxide, and teepol. After each pre-treatment process, the fabrics were thoroughly rinsed with water and dried under ambient conditions prior to the dyeing stage.

2.3 Characterization of solubilized vat dye

The basic characteristics of the solubilized vat blue 5 dye are presented in **Table 1**.

Table 1. Basic characteristics of solubilized vat dyes

Chemical Name	Solubilized Vat Blue 5
Commercial name	Indigosol Blue O4B
CAS Number	2702-33-2
Molecular Formula	$C_{16}H_6Br_4N_2Na_2O_8S_2$
Molecular Structure	

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The solubilized vat blue 5 dye (Indigosol type) used in this study was characterized based on its dye class, solubility behavior, and application characteristics for cellulosic fibers [11]. As a solubilized vat dye, the dye is water-soluble in its leuco sulfate form and undergoes oxidation during the dyeing process to regenerate the insoluble vat dye within the fiber structure [12]. This dye was selected due to its suitability for cellulose-based textiles and its known colorfastness properties.

2.4 Dyeing procedure

Dyeing was carried out on pre-treated and untreated handloom-woven handspun kenaf–cotton fabrics using solubilized vat blue 5 (Indigosol type). All dyeing processes were performed under controlled conditions following a standardized laboratory procedure.

The dye bath was prepared with a dye concentration of 3% owf (on weight of fabric), dissolved in water at room temperature. The material-to-liquor ratio was maintained at 1:30 to ensure uniform dye distribution. Sodium nitrite ($NaNO_2$) at a concentration of 7 g/L was added to the dye bath to promote dye fixation and color development. The fabrics were immersed in the dye solution and dyed at a temperature of 30–40 °C for 30 minutes with continuous agitation to enhance uniform dye penetration into the fiber structure.

After dyeing, the fabrics were subjected to an oxidation process to convert the soluble leuco sulfate form of the dye into its insoluble vat form within the fibers. Oxidation was carried out through exposure to air and sun under ambient conditions. Subsequently, a fixation and neutralization step was performed using a hydrochloric acid solution (10 mL/L) to adjust the fabric pH to neutral. Finally, the dyed fabrics were thoroughly rinsed with water and dried under ambient conditions prior to colorfastness and color performance testing.

2.5 Testing methods

The color fastness properties of the dyed fabrics were evaluated using standardized textile testing methods. Color fastness to washing was assessed in accordance with ISO 105 C06 to evaluate resistance to color change and staining during laundering. Color fastness to rubbing (crocking) was determined following ISO 105 X12 under both dry and wet conditions to assess surface color transfer. Color fastness to perspiration was evaluated according to ISO 105 E04 using acidic and alkaline perspiration solutions to simulate wear conditions. All tests were conducted in compliance with the relevant ISO standards to ensure the reliability and comparability of the results [13].

2.6 Data analysis

Quantitative data obtained from colorfastness and color performance tests were analyzed descriptively and comparatively to evaluate the effects of different pre-treatment methods. Qualitative observations, particularly related to color uniformity and motif sharpness, were analyzed concurrently. A concurrent triangulation approach was employed by integrating quantitative measurements with qualitative assessments to obtain a comprehensive interpretation of the dyeing performance of the fabrics.

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3 Results and discussion

3.1 Results

3.1.1 Characterization of handloom-woven kenaf–cotton fabrics

This study began with the structural characterization of handloom-woven kenaf–cotton fabric to provide technical data as a basis for analyzing the dyeing process. The fabric was produced using a handloom with a plain weave structure, in which cotton yarns were used as warp and kenaf yarns as weft. Plain weave, characterized by an alternating warp–weft interlacing pattern, produces a compact and stable fabric with a relatively smooth surface and good resistance to mechanical stresses.

The handloom-woven fabric exhibited a uniform and stable construction, as reflected by consistent warp and weft densities across the fabric width. The warp density of cotton yarns was 14 ends per inch (5.51 ends/cm), while the weft density of kenaf yarns was 11 picks per inch (4.33 picks/cm). This structural regularity is important for ensuring homogeneous wetting and chemical penetration during pre-treatment, thereby supporting consistent dyeing performance.

Crimp and yarn take-up analyses showed that warp yarns had significantly higher crimp (17.35%) and take-up (14.79%) than weft yarns (2.95% and 2.87%, respectively). This difference is mainly attributed to the higher flexibility of cotton fibers and weaving tension effects compared to the more rigid kenaf fibers. Yarn count analysis further revealed that kenaf weft yarns were considerably coarser (1.96 Nm; 509.95 tex) than cotton warp yarns (3.13 Nm; 319.55 tex), reflecting inherent morphological differences between the fibers [14].

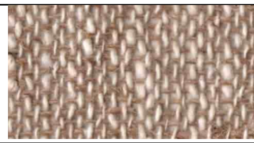
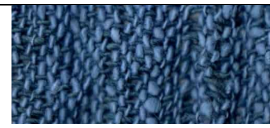
Overall, the combination of coarse yarn structure and the presence of non-cellulosic components in kenaf fibers highlights the importance of effective pre-treatment. Proper scouring and bleaching are essential to improve fiber hydrophilicity and accessibility, thereby enhancing dye uptake, color strength, and uniformity in subsequent dyeing processes.

3.1.2 Pre-treatment and dyeing of handloom-woven kenaf–cotton fabrics

Pre-treatment plays a critical role in the dyeing and printing of textiles, particularly for natural fiber–based fabrics such as kenaf. Owing to its lignocellulosic composition, kenaf fibers possess inherent surface barriers that influence dye uptake. The effects of different pre-treatment conditions on the visual appearance and surface characteristics of the fabrics are summarized in **Table 2**.

The untreated (control) fabric exhibited a dull and non-uniform appearance, with a stiff and slightly rough surface. The natural light-brown color typical of kenaf fibers was clearly visible, indicating the presence of residual natural pigments and surface impurities. Under this condition, the fabric showed limited readiness for subsequent dyeing.

Table 2. Pre-treatment and dyeing results of handloom-woven kenaf–cotton fabrics

Number	Variable of Pre-Treatment	Pre-Treatment Results	Results of Solubilized Vat Blue 5 Dyeing
1	Untreated		
2	Scouring Process		
3	Bleaching Process		
4	Scouring-Bleaching Process		

Following the scouring treatment, noticeable changes in fabric appearance and handle were observed. The fabric became slightly brighter and softer, with reduced stiffness. These changes indicate partial removal of surface impurities, resulting in improved wettability and surface cleanliness, although complete uniformity had not yet been achieved.

Bleaching treatment using hydrogen peroxide produced a more pronounced whitening effect. The natural brownish tone of the fabric was significantly reduced, yielding a cleaner and brighter appearance. This treatment effectively diminished residual pigments and contributed to improved fabric uniformity.

The most pronounced improvement was observed in the combined scouring–bleaching treatment. Fabrics subjected to this treatment appeared the whitest, cleanest, and most homogeneous, with a smooth and flexible surface. This condition indicates a more effective preparation of the fiber structure for subsequent dyeing processes [15].

Additionally, based on **Table 2**, the dyeing results show that untreated fabric exhibits the lowest color depth with uneven coloration due to natural impurities that hinder dye diffusion. Scoured fabric displays a darker shade, indicating improved dye uptake following impurity removal, although slight unevenness remains because of residual natural chromophores. Bleaching only treatment produces a whiter and more uniform fabric particularly in kenaf yarn regions but results in a slightly lighter dyed shade, suggesting partial over-oxidation of reactive sites. The combined scouring–bleaching treatment yields the most uniform and intense coloration, attributed to enhanced fiber porosity and increased accessibility of hydroxyl (–OH) groups. Overall, pre-treatment-induced chemical transformations significantly improve dye absorbency, color uniformity, and dye fixation.

3.1.3 Color fastness test results

The washing fastness results **Table 3** indicate that all dyed handloom-woven kenaf–cotton fabrics exhibit good to excellent color fastness, with ratings ranging from 4–5 to 5. The untreated, scoured, and bleached fabrics show comparable washing fastness values of 4–5, both in terms of color change and staining on cotton and wool adjacent fabrics. Notably, the fabric subjected to combined scouring–bleaching pre-treatment achieves the highest rating (5), indicating no perceptible color change and no staining after washing.

The rubbing fastness results reveal satisfactory performance across all pre-treatment conditions. In dry rubbing tests, all samples demonstrate ratings of 4–5, indicating minimal color transfer. For wet rubbing, the untreated fabric records a slightly lower rating (4), whereas scoured, bleached, and scouring–bleaching treated fabrics consistently achieve 4–5, suggesting improved resistance to color transfer under wet mechanical action.

The perspiration fastness results, evaluated under both acidic and alkaline conditions, show excellent performance. The untreated fabric exhibits ratings of 4–5, while all pre-treated samples (scouring, bleaching, and scouring–bleaching) achieve the maximum rating of 5 on both cotton and wool test fabrics. These results indicate high resistance to color change and staining under simulated perspiration conditions.

Table 3. Color fastness test results of handloom-woven kenaf–cotton fabrics

Pre-Treatment	**Color fastness**								
	Washing			**Rubbing**		**Perspiration**			
	Color fastness	**Stain Cotton**	**Stain Wool**	**Dry Rubbing (Cotton)**	**Wet Rubbing (Cotton)**	**Acid (Cotton)**	**Acid (Wool)**	**Alkaline (Cotton)**	**Alkaline (Wool)**
Untreated	4-5	4-5	4-5	4-5	4	4-5	4-5	4-5	4-5
Scouring	4-5	4-5	4-5	4-5	4-5	5	5	5	5
Bleaching	4-5	4-5	4-5	4-5	4-5	5	5	5	5
Scouring-Bleaching	5	5	5	4-5	4-5	5	5	5	5

3.2 Discussion

This study demonstrates that the dyeing performance of vat blue 5 on handloom-woven kenaf–cotton blended fabric is strongly influenced by both fabric structure and pre-treatment conditions. The balanced plain weave facilitates uniform solution penetration, while differences in yarn crimp and fiber characteristics between cotton and kenaf affect dye accessibility.

Scouring improves dye uptake by removing hydrophobic impurities, although it does not fully eliminate natural pigments in kenaf fibers, which may reduce color uniformity. Bleaching enhances fabric whiteness and visual uniformity but may slightly decrease color depth due to partial oxidation of reactive hydroxyl groups. The combined scouring–bleaching treatment provides the most effective preparation by removing impurities and chromophoric components while maintaining sufficient cellulose reactivity, resulting in improved dye penetration and fixation.

Color fastness results confirm that pre-treated fabrics exhibit excellent resistance to washing, rubbing, and perspiration, whereas untreated fabrics show inferior wet rubbing fastness due to limited dye penetration. With appropriate pre-treatment, kenaf–cotton blended fabrics achieve color fastness comparable to conventional cotton fabrics.

Overall, the novelty of this study lies in identifying combined scouring–bleaching as a critical pre-treatment strategy for achieving optimal dyeing performance and color fastness in kenaf-based blended textiles, supporting their potential as sustainable dyed fabric alternatives.

4 Conclusion

This study confirms that pre-treatment plays a decisive role in determining the dyeing performance of solubilized vat blue 5 on handloom-woven kenaf–cotton fabrics. While scouring and bleaching individually improve dye uptake, their combined application provides the most effective and consistent enhancement by optimizing fiber accessibility and dye fixation. The scouring–bleaching process successfully balances impurity removal and cellulose reactivity, enabling stable dye entrapment and resulting in durable coloration with color fastness comparable to conventional cotton fabrics. By extending established dyeing principles to kenaf-based blended textiles, this study highlights the potential of kenaf as a sustainable alternative for value-added textile applications. Further studies are recommended to evaluate other dye systems and refine processing conditions to advance the practical use of kenaf fibers in textile dyeing.

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