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Characterisation of sustainable knitted apparel produced from linen yarn dyed with natural dyes

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This research aims to characterise knitted apparel produced from linen yarn dyed with natural dyes. In this study, 100 % linen yarn of 40L count is first subjected to chemical softening treatments and then dyed using selected natural dyes. The dyed yarn is evaluated for its values using a spectrophotometer. Tensile tests conducted before and after dyeing indicate that the loss in yarn strength is negligible. The dyed linen yarn is subsequently knitted on a flat knitting machine, and the resulting fabric is assessed for key comfort characteristics, including thermal resistance, moisture vapour transmission rate, and air permeability. The findings show that knitted linen apparel provides comfort properties at an acceptable level, thereby ensuring adequate wearer comfort. In addition, the linen knitted fabrics are tested for essential mechanical properties such as pilling, abrasion, and bursting strength, and the results are reported.

Keywords: Comfort, Knitting, Linen yarn, Natural dye, Sustainable apparel

1 Introduction

Linen is a bast fibre derived from the flax plant (*Linum usitatissimum*), one of the earliest domesticated plants known to human civilisation. The cellulose fibres extracted from the inner stalks of the flax plant are used to produce linen yarns and fabrics[1]. Linen fibres are typically thicker than cotton and vary in length, with many fibres being relatively long. This fibre morphology contributes to the superior strength and durability of linen textiles, which are recognised for their longevity. Although linen is used in diverse textile applications, it continues to play a prominent role in home furnishing[2].

Linen is particularly valued in hot climates due to its excellent moisture absorption and comfort. The yarn is notably strong—approximately 5.5 to 6.5 times stronger than cotton—with thread counts typically ranging from 60 to 150. It also exhibits high elongation and is less prone to breaking. The natural colour of linen varies from grey to yellow, and fibre lengths generally range from 18 to 30 inches[3]. Linen fibres exhibit a smooth, silky texture, contributing to their pleasant handle. The fibre has a specific gravity of 1.50 and reflects heat and light effectively, while also demonstrating good resistance to sunlight. Linen yarns are commonly measured in "lea," defined as the number of yards per pound divided by 300; for instance, a yarn of 1 lea produces 300 yards per pound[4].

The introduction of synthetic dyes in 1856 resulted in a sharp decline in the use of natural dyes. By the early twentieth century, the low cost and convenience of synthetic dyes led to their widespread adoption. Today, global synthetic dye consumption is estimated to be nearly ten million tonnes annually. The production and application of these dyes generate substantial amounts of chemical waste and unfixed dyes, contributing to environmental pollution and posing potential health risks[5-7]. Indian madder (Rubia cordifolia) is a perennial climbing plant native to the Indian subcontinent and has been cultivated for centuries for its characteristic red dye, extracted from its roots[8]. The plant grows as a perennial climber and has been traditionally used in the dyeing process. The primary Colouring compound, alizarin, has endowed Indian madder with cultural and historical significance in traditional Indian textiles and Ayurvedic practices[8-10]. This natural dye source represents a sustainable alternative to synthetic dyes, which are known to generate substantial chemical waste and pose environmental concerns[11].

Linen offers several sustainability benefits as a textile material. It requires less water and pesticides compared to cotton, making it an environmentally friendly choice[12]. Additionally, linen possesses

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inherent desirable properties, like high strength[13]. However, linen yarn typically exhibits low flexibility, making it unsuitable for knitting without prior softening treatments[14]. The interaction between these necessary chemical softening processes and subsequent natural dyeing applications remains an area that requires investigation.

Previous studies on natural dyeing have focused on fastness and dye uptake on various substrates[15]. However, comprehensive research evaluating the entire process chain, from yarn softening and natural dyeing to knitting and final fabric assessment, is notably lacking. Specifically, there is limited understanding of how these combined processes affect the essential comfort and mechanical properties of the resulting knitted linen fabric[16]. Many natural dyes, including those from plant sources such as Indian madder, also impart additional functional benefits, such as UV protection and antimicrobial activity, which could enhance the value of the final apparel product[17-20].

Recent studies have further highlighted the growing industrial interest in sustainable dyeing and eco-functional textile development. It has been demonstrated that natural dyeing protocols can be optimised to enhance depth while maintaining fibre strength[21]. Findings also indicate that eco-efficient wet-processing techniques can improve the mechanical behaviour of knitted fabrics without compromising comfort[22]. Additional studies report that plant-based dyes are capable of imparting functional properties such as UV resistance and antimicrobial activity, thereby increasing fabric performance[23]. Furthermore, investigations confirm that integrating natural dyeing with fabric-engineering strategies can enhance durability and wearer comfort, supporting the commercial potential of naturally dyed knitted garments[24].

This study aims to address these research gaps by developing and characterising knitted linen apparel produced from yarn that undergoes both chemical softening and natural dyeing with Indian madder. The specific objectives are to assess the effect of softening treatment on the properties of linen yarn, evaluate the characteristics and fastness of the naturally dyed yarn, produce knitted fabric from the processed yarn, and comprehensively characterise the resulting fabric's comfort properties and mechanical performance. This integrated approach offers a comprehensive evaluation of sustainable knitted linen apparel, advancing eco-friendly textile manufacturing practices.

2 Materials and Methods

2.1 Materials

The raw materials used for developing the knitted linen apparel were sourced from textile units in Tamil Nadu. Linen yarn of count 40 lea was procured from a linen weaving industry. Oxylube YL, a yarn lubricant, was used as the softening agent. The natural dyeing ingredients—Indian madder, alum (used as a mordant), soapnuts, and ash water (used as scouring agents)—were obtained from M/s Ayurvastra Thanga Naturals, Kotaipalayam, Coimbatore, India.

2.2 Methods

The experimental procedures comprised yarn softening, natural dyeing using aqueous extraction, and flat knitting for garment construction. Yarn pre-treatment was performed using an RKTex machine with a 5 kg capacity. Natural dyeing was performed at M/s Ayurvastra Textiles, Erode, India.

2.2.1 Softening

Linen yarn typically exhibits low flexibility, making it unsuitable for knitting without prior softening. Oxylube YL was applied as an emulsion to improve flexibility. The emulsion contained particles ranging from 300 to 10,000 nm, enabling deposition between fibres and replacing the natural wax lost during earlier processing. This physical deposition of lubricant enhanced the pliability of the yarn and facilitated subsequent knitting.

2.2.2 Dyeing

Soapnuts, rich in saponin glycosides, were used as a natural desizing agent. Their surfactant properties enabled the removal of starch and wax-based sizing materials. Ash water, prepared by soaking wood ash in water, served as a natural scouring agent due to its mild alkalinity, helping to neutralise impurities and residual acids.

For mordanting, alum was boiled for 30 min at 60 °C and then added to the dye bath. The mordant bath was maintained at 50 °C for 30 min to facilitate strong binding between the dye molecules and the yarn. The extracted dye bath was boiled at 100 °C for 1 h. After dyeing, the hank was removed and washed thrice in cold water. A final wash was carried out in 40 °C water containing 100 g soapnut extract, after which the yarn was dried for one day.

2.2.3 Extraction of Dye from Indian Madder

Approximately 300 g of *R. cordifolia* dried roots were crushed and boiled in water for 1 h at 100 °C to extract the dye. The yarn was converted from cone to hank form prior to dyeing. Trials conducted between 30–80 °C revealed that a temperature of 50 °C produced the deepest shade when the yarn was boiled for 30 min. Thus, all dyeing experiments were standardised at 50 °C for optimum depth.

2.3 Testing

2.3.1 Single Yarn Tensile Testing

Tensile properties of monofilament, multifilament, and spun yarns were evaluated according to ASTM D2256 using an Instron 3345 tensile tester at KCT TIFAC-CORE NFRC (Natural Fibre Research Centre) facilities. The method measured maximum force and elongation, enabling calculations of breaking tenacity and modulus.

2.3.2 Friction Testing

Yarn friction was measured using a dynamic friction tester following ASTM D3108/M-13 (2020). The instrument determined the coefficient of dynamic friction by quantifying resistance as the yarn slid over a standard surface, providing insight into yarn behaviour during knitting.

2.3.3 Pilling Resistance

Pilling resistance was assessed using a random tumble pilling tester in accordance with ASTM D3512. Tests were conducted under standard atmospheric conditions to ensure reliable evaluation of surface deterioration and appearance retention.

2.3.4 Bursting Strength

Bursting strength, essential for knitted fabrics and technical textiles, was measured using the diaphragm method specified in ASTM D3786. The test determined the force required to rupture the fabric and recorded its ultimate elongation.

2.3.5 Spectrophotometric Analysis

Colour measurements were performed using a Gretag Macbeth Colouri 5 spectrophotometer (Model: Colouri 5) in accordance with ASTM C1510. Spectrophotometry was used to assess values and reflectance behaviour across the wavelength range of 400-700 nm at 10 nm intervals, enabling both qualitative and quantitative evaluation of the dyed yarns.

2.3.6 Colour Fastness to Washing

Colour fastness to washing was tested according to ISO 105:C06/2010. Samples were washed at 40 °C for 30 min using a mechanical washing process, and changes in and staining were assessed.

2.3.7 Fastness to Crocking

Colour fastness to rubbing was evaluated using AATCC Method 8-2013. Each specimen was rubbed with a white crocking cloth under controlled conditions in both dry and wet states. The degree of staining on the crocking cloth was assessed using the Grey Scale for Staining, and ratings were assigned accordingly. Two separate specimens were used for the test—one for dry rubbing and one for wet rubbing. Specimens measuring at least 50 × 130 mm (2.0 × 5.1 in.) were prepared and positioned appropriately for testing. Afterward, the staining was compared against the grey scale to determine the final rating.

2.4 Knitting

Knitting was carried out using a 14-gauge advanced flat knitting machine (Shima Seiki) at a facility in Tirupur. A U-neck T-shirt pattern was developed using Shima Seiki design software, and the flat knitting machine was used to produce the front, back, and sleeves with rib structures. The garment was constructed in Kids' size 4 (S). The overall stepwise process involved in the garment development, from softened yarn to the finished garment, is presented in Fig. 1.

3 Results and Discussion

3.1 Properties of Knitted Fabric

The physical properties of the knitted linen fabric indicate that it is produced using 40L yarn and has a

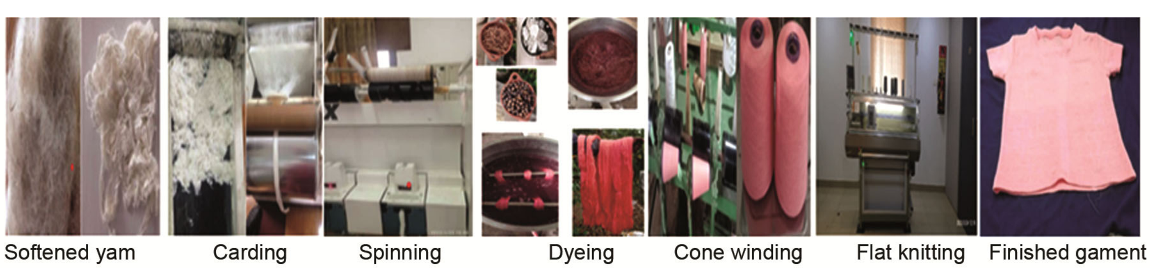

Fig. 1 — Stepwise process involved in garment development

GSM of 240 g/m². The loop length is 2.7 cm, with 17 courses per inch (CPI) and 16 wales per inch (WPI), resulting in a stitch density of 272. The tightness factor is calculated as 2.3, indicating a moderately tight-knit structure. The loop shape factor is 1.3, indicating balanced proportions between the course and wale dimensions. These parameters collectively define the structural compactness and mechanical behaviour of the knitted sample.

3.2 Tensile Strength Analysis of Linen Yarn

Table 1 displays the tensile properties of the yarn before and after softening. It shows that the softened yarn records a 9.4 % reduction in tensile strength and a 4 % reduction in elongation compared with the raw yarn. However, these decreases are relatively minor and do not adversely influence the knitting performance, demonstrating that the softening treatment is suitable for preparing linen yarn for knitting applications.

3.3 Effect on Softening Yarn Friction

The frictional behavior of linen yarn is influenced by the application of softening agents. After softening, the yarn exhibits a lower coefficient of friction (0.154) compared with the untreated yarn (0.247), indicating improved surface smoothness. Softening agents, particularly cationic silicone softeners, reduce surface friction and improve yarn smoothness. This reduction enhances yarn mobility during knitting and significantly improves yarn knittability[1].

3.4 Abrasion Performance of Softened Linen Yarn

Abrasion resistance is strongly affected by fibre type, fineness, and length. Fibres with high elongation, elastic recovery, and work of rupture generally exhibit better abrasion resistance[8]. Figure 2 illustrates the differences in abrasion behaviour between untreated and treated yarns. The abrasion behaviour of the yarn clearly indicates the effect of the softening treatment. The treated yarn exhibits substantially lower abrasion resistance than the untreated yarn, as evidenced by a marked reduction in the number of abrasion strokes sustained before failure. On average, the treated yarn withstands only 83 abrasion strokes, compared to 186 strokes for the untreated yarn, while the maximum and minimum values also show a similar declining trend. This reduction in abrasion resistance can be attributed to the softening treatment, which, although essential for improving knittability, slightly weakens the yarn structure. The inherent fibre characteristics further contribute to this behaviour: linen fibres possess relatively low tenacity (0.54 N/tex), limited breaking extension (3.0%), and a low work of rupture (8.0 mN/tex), which collectively make them less resistant to repeated mechanical stress. The contrasting abrasion behaviour of the untreated and treated yarns is visually evident from the abrasion images, which highlight more pronounced damage in the treated yarn.

3.5 Pilling Resistance of Knitted Linen Fabric

Linen fibres are naturally long and therefore have a low inherent tendency to pill[8]. Regarding surface durability, the pilling performance of the knitted linen fabric remains acceptable. Owing to the naturally long fibre length of linen, the tendency for pilling is inherently low. The fabric records an average pilling grade of 3.3, corresponding to moderate to slight pilling. The minor pilling observed is likely a consequence of the softening and natural dyeing treatments, which may slightly loosen surface fibres. Nevertheless, the overall surface appearance of the fabric remains satisfactory.

Table 1— Tensile properties of linen yarn before and after softening treatment

Property	Maximum load, kg			Extension at maximum load, mm		
	Before	After	%, change	Before	After	%, change
Coefficient of variation	13.29	14.36	-9.4	4.35	10.38	-4
Maximum	1.00	0.76		5.20	5.20	
Mean	0.85	064		4.91	4.77	
Median	0.81	0.65		4.80	5.07	
Minimum	0.734	0.53		4.73	4.20	
Range	0.27	0.23		0.476	1.00	
Std. deviation	0.11	0.09		0.21	0.50	

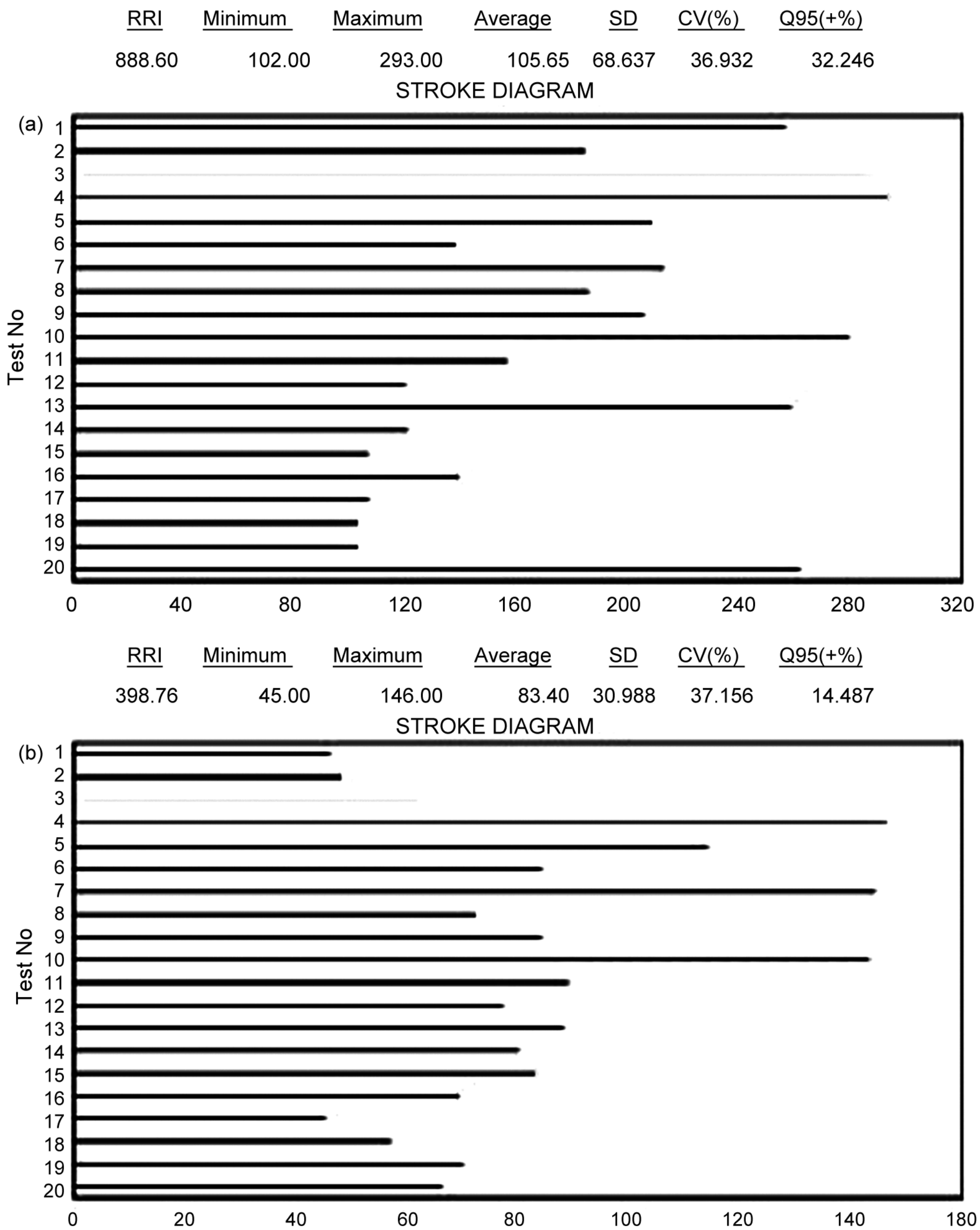

Fig. 2 — Abrasion of (a) untreated, and (b) treated yarn

3.6 Bursting Strength of Knitted Linen Fabric

The bursting strength results demonstrate that the knitted linen fabric is capable of withstanding multidirectional stresses effectively. The fabric shows an average bursting strength of 4.10 kg/cm², indicating adequate structural integrity for apparel applications. This performance can be attributed to the intrinsically high strength of linen fibres, and this translates into good bursting strength in the knitted structure. Furthermore, the tightness factor of 2.3 enhances inter-loop cohesion, thereby contributing to the improved bursting behaviour.

3.7 Spectrophotometric Strength Analysis

Spectral analysis reveals that the naturally dyed linen yarn achieves a higher absorbance (K/S value of 0.93) compared with the standard (0.38). This spectrophotometric strength (K/S) is graphically represented in Fig. 3. The strength (245.89) confirms that Indian Madder dye shows good affinity towards

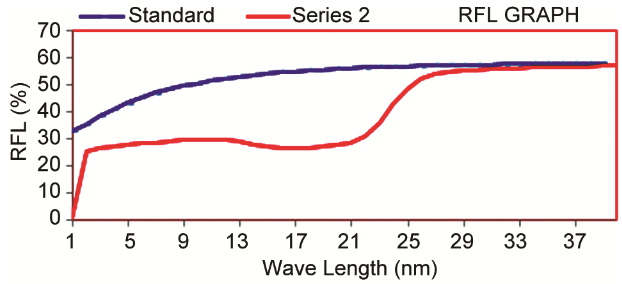

Fig. 3 — Spectrophotometric strength (K/S) graph

linen, with enhanced dye uptake in the UV region. This demonstrates the suitability of Indian Madder as a natural dye for linen yarns.

3.8 Fastness to Washing

The fastness to washing of the naturally dyed linen yarn was evaluated, and the results are presented in Table 2. The yarn exhibits wash fastness ratings in the range of grade 3 to 5, indicating overall good resistance to change and staining. Minimal staining is observed on synthetic fibres such as acetate, polyester, and acrylic (grades 4–5), whereas moderate staining is noted on cotton and wool (grades 3–4). Nylon shows comparatively better resistance, with a staining grade of 4. These results suggest that the naturally dyed linen yarn demonstrates satisfactory wash fastness, with stronger dye–fibre interactions observed particularly with synthetic substrates.

3.9 Fastness to Rubbing

The fastness to crocking (rubbing) of the naturally dyed linen fabric was assessed under dry and wet conditions, and the results are summarised in Table 3. The fabric exhibits excellent resistance to transfer in dry rubbing, achieving a rating of 4–5, which indicates negligible staining and confirms strong dye–fibre affinity. Under wet rubbing conditions, a slight reduction in fastness is observed (grade 4), which can be attributed to fibre swelling and increased dye mobility in the presence of moisture[17]. Nonetheless, the crocking fastness values obtained are considered acceptable for apparel and textile applications.

4 Conclusion

The research study on naturally dyed linen yarn using Indian madder for making sustainable apparel has yielded remarkable results, highlighting the potential of natural dyes in supporting sustainability within the textile industry. The yarn finished with YL gives excellent handling improvement due to the specially formulated micro wax emulsion. The product shows excellent adhesion on the fibres. Therefore, no abrasion occurs during further processing. As a result, knitting performance increases. Softening linen yarn for knitting offers numerous advantages that enhance both the knitting process and finished products. The linen Yarn was naturally dyed using Indian Madder, which is valued for its anti-inflammatory and antimicrobial properties. A knitted fabric was then made. The quality assessment was conducted using a UV Spectrophotometer, and included tests for pilling resistance, bursting strength, Colour fastness, and rubbing fastness. The outcome of the above assessment was found to be good, and hence, the knitted linen fabric is recommended for making apparel with high quality, comfort, and aesthetically pleasing garments. The outcome of this research demonstrates that the textile industry has immense potential for producing sustainable, naturally dyed knitted apparel.

Table 2 — Colour Fastness to washing rate

Specification	Grade
change (pink)	3-4
Staining on Acetate	4-5
Staining on Cotton	3-4
Staining on Nylon	4
Staining on Polyester	4-5
Staining on Acrylic	4-5
Staining on Wool	4

Table 3 — Colour fastness to crocking (rubbing)

Rubbing condition	Dry	Wet
Rating	4-5	4

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