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Dyeing Tencel Fabric with *Azadirachta Indica* Leaves and Mordanting with Potassium Aluminium Sulphate and *Citrus Limon* Extract for Enhanced Fastness Properties

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ABSTRACT

Amidst mounting concerns regarding the health and environmental repercussions associated with synthetic agents, there has been a burgeoning interest in the exploration of natural dyes as a safer alternative. Derived from minerals, plants, and animals, these natural dyes have gained substantial traction due to their perceived eco-friendliness and reduced health risks compared to their synthetic counterparts. Notably, our study revealed significant enhancements in fastness properties across all mordanted samples, while those left un-mordanted exhibited notably inferior fastness properties. Among the mordants under investigation, potassium aluminium sulphate demonstrated appreciable stability characteristics, yet Citrus limon extract emerged as an even more effective mordant than potassium aluminium sulphate. The study also delved into evaluating the colour strength properties of the test samples, providing a comprehensive analysis of the Tencel fabric's overall dye performance and adherence to industry standards. In this research, a natural dye was extracted from the leaves of Azadirachta indica which was applied to Tencel fabric, which was then meta-mordanted with potassium aluminium sulfate and Citrus limon extract. The study explored various dyeing parameters, including diverse dye concentrations (7 g), dyeing temperatures (35, 50, and 65 °C) with a precision of ±1 °C, and dyeing durations (40, 55, and 75 minutes). The resulting samples were then subjected to testing against fastness properties, including washing fastness (ISO 106 C06), rubbing fastness (AATCC 8), perspiration fastness (ISO 105 E04) and Colour strength (K/S) of the Tencel fabric. The assessment of fastness properties was carried out using a grey scale.

KEYWORDS

Tencel fabric, dyeing, mordanting, fastness, Azadirachta indica, Citrus limon, Potassium aluminium sulphate

INTRODUCTION

The textile industry uses dyes more than any other industry. Almost half of the dyes are used in the process of making textiles, and 10–15% of those dyes find their way into effluents, occasionally reaching as high as 35-40%. Highly coloured chemicals with high oxygen requirements in both chemical and biological processes are used in dyeing industry effluents. Due to their poisonous, carcinogenic, and allergic effects, these dye-containing effluents can harm both people and aquatic life in natural water bodies [1]. In addition, toxic dye-containing effluents can have a devastating effect on the air quality. To mitigate the effects of dye-containing effluents, governments around the world have put in place strict regulations and standards for effluent discharge from industries [2]. The impact of their waste is particularly concerning. These waste products often take the form of harmful and undesirable substances, which pose significant challenges to the environment. They not only harm the atmosphere but also have detrimental effects on agricultural land and water bodies, all of which play a crucial role in the textile production process. Textile waste, including chemicals and dyes, contributes to the pollution of the atmosphere as emissions from manufacturing processes release harmful pollutants into the air. These pollutants can have wide-ranging consequences, from deteriorating air quality to contributing to climate change. Additionally, textile waste that ends up in landfills or is improperly disposed of can lead to soil contamination and affect the quality of agricultural land [3]. Harmful chemicals and non-biodegradable materials from textiles can seep into the soil, rendering it unsuitable for farming and posing a risk to both crops and the health of those working on the land. Water bodies also suffer as textile waste, often containing toxic chemicals and dye residues, finds its way into rivers, lakes, and oceans. This contamination not only harms aquatic ecosystems but can also disrupt the delicate balance of these environments, affecting the health and survival of aquatic life [4]. Furthermore, the presence of these pollutants in water bodies can have far-reaching consequences, including the development of serious diseases and cancers in both aquatic organisms and humans who rely on these water sources. In sum, the textile industry's waste, in the form of harmful and undesirable substances, has a detrimental impact on the environment, with far-reaching consequences for the atmosphere, agricultural land, and water bodies. Addressing these issues is crucial for preserving both the environment and the sustainability of the textile industry itself [5]. Natural dyes, enzyme-based dyes, and reactive dyes, as well as standards for managing wastewater, are used to dye clothes in a way that is safe and good for the environment. This helps cut down on pollution in the environment [6]. Natural colours derived from plants are gaining more reception due to their therapeutically soothing and non-toxic nature. These dyes have greater biocompatibility with the ecosystem and do not pose any disposal problem. Plant-based dyes have excellent antioxidant, anti-inflammatory, analgesic, anticancer, and antibacterial properties in addition to acting as remedies for many illnesses [7-8]. Natural dyes are widely used in textiles, food, pharmaceuticals, solar cells, leather, sportswear, and cosmetics because of their exceptional properties. Therefore, the resurgence of natural dyes is being welcomed by the worldwide community in various applied fields [9-10]. The use of natural dyes and bio-mordants in the textile industry is gaining increasing attention and recognition for its multifaceted benefits. Natural dyes, derived from plant sources, insects, or other organic materials, offer a sustainable and eco-friendly alternative to synthetic dyes. In addition to their environmental advantages, natural dyes also possess various medicinal properties that have the potential to positively impact human health [11]. One of the primary advantages of natural dyes is their potential to help with a wide range of ailments. Many natural dyes have been used in traditional medicine and herbal remedies for centuries. For example, plants like turmeric and indigo have been known for their anti-inflammatory and antimicrobial properties. When these natural dyes are used in textiles, they can come into contact with the skin, potentially providing therapeutic benefits to the wearer [12]. This means that clothing dyed with natural dyes can serve a dual purpose – not only as a fashion statement but also as a form of wearable therapy, particularly relevant in the context of skin-related conditions or allergies. To enhance the colourfastness properties of fabrics dyed with natural dyes, bio-mordants come into play. Bio-mordants are substances, often derived from natural sources, that are used to improve the adherence of the dye to the fabric. In doing so, they help ensure that the vibrant colours produced by natural dyes remain intact even after multiple washes and extended use. This aspect is crucial for the fashion industry, as it contributes to the longevity and durability of clothing items. What makes bio-mordants particularly exciting is their dual role in benefiting both the environment and human health. These bio-mordants not only serve as functional molecules to enhance dye adherence but also carry their own set of bio-medico characteristics. These characteristics can range from being antimicrobial, hypoallergenic, or even having therapeutic effects on the skin [13]. As a result, clothing dyed with bio-mordants not only maintains its colour quality but also imparts health benefits to the wearer. The increasing popularity of bio-mordants in textiles reflects the growing awareness of sustainable and eco-friendly practices within the fashion and textile industry. Consumers are becoming more conscious of the environmental impact of their clothing choices and are also valuing products that offer additional health-related advantages. This trend is beneficial not only from a business perspective but also for the community at large, as it encourages the use of natural, sustainable, and health-promoting materials in everyday clothing [14].

The neem tree (*Azadirachta indica*) is a native of the Indian subcontinent. It has been used since ancient times to treat a variety of human ailments, as well as for other hygienic purposes [15]. The medicinal and disinfectant actions of the *Azadirachta indica* tree have been well-described since ancient times. Neem is used to make a variety of beneficial products, including anti-malarial, spermicidal, anti-tuberculosis, antipyretic, anti-viral, anti-fungal, and anti-allergic drugs [16]. The Neem tree is a natural air filter, and it has been recommended that planting Neem trees along roadsides is an efficient strategy to control pollution from traffic. The tree can live in an urban environment polluted with toxins from traffic. As a result, it can be an important species for greenbelts in urban and industrial areas [17]. The Neem tree promotes the growth of other trees in arid areas by enhancing soil fertility and preventing the wind from eroding valuable topsoil, especially in the winter [18]. Terpenes and limonoids are two of neem's primary chemical components. Among the most potent active compounds found in limonoids are azadirachtin, 3-deacetyl-3-cinnamoylazadirachtin, [-tigloyl-3-acetyl-II-methoxyazadirachtin, 22, 28-dihydro-23B-methoxyazadirachtin, nimbanal, 3-tigloylazadirachtol, 3-acetyl-s Isoazadirolide, nimbonone, nibonolone, and Margosinone are examples of terpenoids. Neem improves the liver's capacity to cleanse itself of toxic pollution by increasing Glutathione-s-transferase production [19-20].

An important part of the natural dyeing process involves mordants. The colourfastness of textiles is being improved, using both chemical and natural mordants. Consequently, transition metal salts and chemical mordants such as Fe, Cu, Mu, and others are used as mordants in natural dyeing. While chemical mordants are generally more effective, they also cause some harm to the environment [21-22]. Heavy metal ions from mordants, including chromium, iron, cobalt, nickel, copper, or aluminium, were present, and their residuals in dyeing wastewater provide a serious waste management problem. Natural mordants have been proposed as an effective and environmentally friendly solution to this problem. Many of the tannic acids found in natural mordants are responsible for enhancing the fastness property of textiles [23]. Alum (potassium aluminium sulphate) and lemon (*Citrus limon*) are used in this test.

A member of the Rutaceae family, *Citrus limon* is a small tree with edible yellow fruits and evergreen leaves [24]. The fruit, in particular the juice and essential oil extracted from it, serves as the primary raw material for *Citrus limon*. Although the *Citrus limon* fruit stands out for having well-known nutritional qualities. Before the discovery of vitamin C, *Citrus limon* fruit juice was historically used as a treatment for scurvy [25]. *Citrus limon* essential oil was used to treat coughs in ancient Romanian medicine. Besides being rich in vitamin C, which helps ward off infections, the juice has been used traditionally to treat scurvy, high blood pressure, sore throat, arthritis, fever, and chest pain. The chemical diversity of *Citrus limon* determines its medicinal potential. The most important class of secondary metabolites in the fruit includes flavonoids and other substances, including phenolic acids, coumarins, carboxylic acids, amino acids, and vitamins. Monoterpenoids, especially D-limonene, make up most of the constituents of an essential oil [26]. Potassium aluminium sulfate is a metallic mordant that is used to fix the dyes on fabrics. Potassium aluminium sulfate has been used as a dye fixative since antiquity and is especially popular in traditional Japanese dyeing techniques.

In this study, natural dyes were pushed as being good for the environment, and both natural and metallic mordants were used to make the dyes more stable. *Azdirachta indica* dried leaf powder was used to dye Tencel fabric. Tencel fabric is a new-generation fabric. It is made from wood cellulose and some synthetic substances. Natural and metallic mordants were used in the research to compare the two binders for their dye fastness properties on Tencel fabric. Metallic mordants harm the environment, so they should be replaced with natural mordants. Because natural mordants have a positive environmental impact, they are biodegradable and non-toxic. The purpose of this research was to determine the effectiveness of natural mordants in improving the fastness properties of Tencel fabric at various times and temperatures compared to a conventional metallic mordant. The goal of this research, which employs mordants such as Potassium aluminium sulfate and citric acid, is not only to improve the fastness properties of Tencel fabric but also to discover an environmentally friendly and sustainable alternative mordant.

EXPERIMENTAL

Materials and Methods

Ready-to-dye Tencel fabric used in this study was purchased from Shahi Exports Pvt. Ltd. The leaves of the *Azadirachta indica* tree were collected at the Mody University of Science and Technology campus in Laxmangarh, Rajasthan. The fresh *Azadirachta indica* leaves are collected from the tree, and then the leaves are washed with water to get rid of any dust and other contaminants. The washed leaves were dried in the shade at room temperature. The dried *Azadirachta indica* leaves were ground using a blender and made into a fine powder. Tencel fabric was mordanted with potassium aluminium sulphate as well as *Citrus limon* mordant. The potassium aluminium sulphate and *Citrus limon* were bought at a Sikar market. Potassium Aluminium sulfate was used in powder form, and *Citrus limon* juice was used.

Table 1. Fabric specification

Fabric composition	Fabric type	Fabric structure	Fabric GSM, g/m^2	EPI, ends/cm	PPI, ends/cm
Tencel	Woven	Plain weave	95	45	26

Aqueous extraction

An aqueous extraction method was used to extract the dye from the dried leaves of *Azadirachta indica*. This method involves boiling the leaves in a solution of water and then filtering out the impurities to obtain a dye-infused liquid. To extract the dye from powdered dried leaves of *Azadirachta indica*, 300 ml of water was taken in a beaker, and the water was heated on a heating plate until it reached 60 °C. The dye powder was added to the beaker when the temperature of the water reached 60 °C, and it would now be boiled until 200 ml of the dye solution remained in the beaker. After this, the solution is filtered twice through filter paper, and the dye solution is ready for dyeing.

Mordanting Method

In this research, the meta-mordanting method was used to improve the fastness property of Tencel fabric. To mordant the samples, 1.5 g of Potassium aluminium sulfate and 16 ml of *Citrus limon* juice were taken in 200 ml of dye solution. The meta-mordanting method was used to increase the strength and fixation of the dye molecules onto the fabric, creating a more vibrant and durable colour.

Dyeing Procedure

The samples of Tencel fabric (9 g) were taken for the research. For dyeing the samples 200 ml of dyeing solution was used with 1.5 g of Potassium aluminium sulfate and 16 ml of *Citrus limon* juice was used for meta mordanting process in dyeing. *Citrus limon* juice was added to the dyeing solution when the pH balance was 2.5 and after adding the Potassium aluminium sulfate the pH balance of the dyeing solution was 6. The exhaust dyeing process was performed on the beaker dyeing machine. The temperature was raised at a rate of 2 °C per minute. For each combination of temperature ±1 °C (35, 50, and 65 °C) and time (40, 55, and 75 minutes) the equipment was programmed to a dyeing sample. After dyeing the sample was washed with soap, and hot and cold water then dried in the shade at room temperature.

Table 2. Dyeing factors of Tencel fabric

Fabric Dyeing factor	Low Value	Middle Value	High Value
Temperature (°C)	35	50	65
Time (min)	40	55	75
Dye concertation (g)	7	7	7

Colour *fastness assessment*

The colour fastness of dyed fabric was evaluated for their rubbing, washing and perspiration fastness properties according to the standards Washing fastness: ISO 106 C06:2010 (B1M), Rubbing fastness: AATCC 8, Perspiration Fastness: ISO 105 E04. The rate for colour changes on a score from 1 (very poor) to 5 (excellent) was observed. Colour strength (K/S) value, reflectance (%) and CIEL*a*b* values of dyed Tencel fabric.

Washing fastness: ISO 106 C06: 2010 (B1M)

Washing fastness is an important measure of the textile dyeing process's performance, as it determines how well a fabric retains its colour when washed. The washing fastness method used to test the samples was ISO 106 C06 (B1M). For this experiment, a 4x10 cm sample of dyed fabric was used, which was attached to a multifibre swatch. The sample was washed in a washing fastness tester machine at 50 °C for 30 minutes. After washing the sample, the staining of the multifibre sample was evaluated using ISO 105 A03 (greyscale).

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Rubbing fastness: AATCC 8

The colour change that occurs when a textile is rubbed against another material determines its rubbing fastness. Wet and dry rubbing fastness are tested to ensure that the colour of the fabric does not transfer onto other materials during normal wear or when exposed to water. In this research, the test was carried out according to the AATCC 8 test method, which involved rubbing Tencel fabric against 100% cotton and then observing the colour change. The colourfastness of the 100% cotton swatch was evaluated using ISO 105 A03 (greyscale).

Perspiration Fastness: ISO 105 E04

The perspiration fastness of a fabric is an important factor in determining its performance. The "perspiration fastness" of a fabric refers to its ability to resist discolouration or damage due to perspiration and moisture. To test the perspiration fastness of Tencel fabric, ISO 105 E04 was used. Acidic and alkaline solutions were applied to the fabric in this method, and staining on the multifibre was evaluated. The stain-on-multifibre sample was evaluated according to the standard ISO 105 A03 (greyscale).

Colour strength (K/S)

Colour strength (K/S) is the most important parameter to test the quality measurement of a sample in terms of the depth of the colour-dyed fabric. A 650TM spectrophotometer was used to test the L*, a*, b*, c*, h0, and K/S values of all dyed Tencel fabric samples. Everyone used to compare colour values using the CIE L*a*b* or CIELAB colour scales. The terms L*, a*, and b* denote brightness or lightness, redness or greenness, yellowness, or bluishness, etc. While positive a* is red and negative a* is green, positive b* is yellow and negative b* is blue.

The reflectance (%) of the dyed fabric samples was measured by using a Data colour 650 TM spectrophotometer. The strength of any colourant (dyestuff/pigment) is related to absorption property.

Equation of colour strength (K/S):

$$\mathrm{k/s} = \frac{(1-\mathrm{R})\times 2}{2\mathrm{R}} \tag{1}$$

where R is the reflectance; K is absorbance and S is the scattering.

RESULTS AND DISCUSSION

Dyeing under optimized conditions

Neem dry leaves extract was used to dye Tencel fabric according to Table 3. To increase the fastness properties of the fabric, Potassium aluminium sulfate and *Citrus limon* extract were used. The samples were coded according to the table 3.

Table 3. Samples dyeing different conditions

Samples coding No.	Temperature (°C)	Time (min)	Dye concertation (g)
S1	35	40	7
S2	35	55	7
S3	35	75	7
S4	50	40	7
S5	50	55	7
S6	50	75	7
S7	65	40	7
S8	65	55	7
S9	65	75	7

Fastness properties of Tencel fabric mordanting with Potassium aluminium sulfate and *Citrus limon*

Washing fastness

In this study, it was found that Potassium aluminium sulfate and *Citrus limon* mordants had a significant effect on the washing fastness property of Tencel. Not only the mordants but also the time and temperature played an important role in improving the washing fastness property of Tencel fabric. Without mordant, the washing fastness of Tencel did not increase significantly, as shown in Table 4. According to the study's findings, mordanting Tencel fabric was essential for improving its washing fastness. *Citrus limon* and Potassium aluminium sulfate mordant both had excellent washing fastness, but *Citrus limon* had greater stability than Potassium aluminium sulfate mordant due to its lower pH. During the meta-mordanting process, the time and temperature were increased, resulting in a significant improvement in washing fastness. Excellent washing fastness was achieved at higher dyeing times and temperatures. However, even at the shortest dyeing times and temperatures, good laundry fastness was discovered. The results of washing fastness are shown in Table 4. The comparison of fastness properties on various fibres is shown in Tables 4 a, b and c.

Table 4a. Washing fastness of Tencel fabric on cotton fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.0	4.5	5.0
S2	2.0	4.5	5.0
S3	2.0	4.0	4.5
S4	2.0	4.5	5.0
S5	2.5	4.5	4.5
S6	2.5	4.5	5.0
S7	2.5	4.5	5.0
S8	2.5	4.5	5.0
S9	2.5	4.5	5.0

Table 4b. Washing fastness of Tencel fabric on acrylic fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.5	5.0	5.0
S2	2.5	5.0	5.0
S3	2.5	5.0	5.0
S4	2.5	5.0	5.0
S5	2.5	4.5	5.0
S6	2.5	5.0	4.5
S7	3.0	4.5	5.0
S8	3.0	5.0	4.5
S9	3.0	5.0	5.0

Table 4c. Washing fastness of Tencel fabric on wool fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.0	4.5	5.0
S2	2.0	4.0	4.5
S3	2.5	4.5	4.5
S4	2.5	4.5	5.0
S5	2.5	4.5	4.5
S6	2.5	4.5	5.0
S7	2.5	5.0	5.0
S8	3.0	5.0	5.0
S9	2.5	5.0	5.0

Rubbing fastness

In this research, it was found that both of the mordants Potassium aluminium sulfate and *Citrus limon* have a significant effect on the wet and dry rubbing fastness of Tencel fabric. The dyeing time and temperature, these factors also had a great impact on the wet and dry rubbing fastness properties. Potassium aluminium sulfate and *Citrus limon* mordants caused a significant increase in the wet and dry rubbing fastness of Tencel fabric compared to untreated samples. With increasing the dyeing time and temperature the rubbing fastness properties were increased. This can be seen in Table 5a and 5b which shows that the fabrics dyed with Potassium aluminium sulfate and *Citrus limon* mordants had a higher wet and dry rubbing fastness than those that were untreated.

Table 5a. Dry rubbing fastness of Tencel fabric

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.5	4.0	4.5
S2	3.0	4.5	4.5
S3	3.0	4.0	4.5
S4	2.5	4.5	4.5
S5	3.0	4.0	4.5
S6	3.0	4.5	4.5
S7	3.0	4.5	5.0
S8	3.5	4.5	5.0
S9	2.5	5.0	4.5

Table 5b. Wet rubbing fastness of Tencel fabric

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.0	3.5	3.5
S2	2.0	3.5	3.5
S3	2.5	4.0	4.0
S4	2.5	4.0	4.0
S5	2.5	3.5	5.0
S6	2.5	3.5	5.0
S7	2.5	4.5	5.0
S8	2.5	4.5	5.0
S9	2.5	5.0	5.0

Perspiration Fastness

Tencel fabric's perspiration resistance was a great result. The time, temperature, and mordants had a significant impact on the perspiration fastness of the fabric. As the dyeing temperature and time were increased, the fabric's perspiration-fastness improved. Tencel fabric's acidic and alkaline perspiration fastness properties were improved by Potassium aluminium sulfate and *Citrus limon* mordants. Un-mordanted dyed Tencel fabric, on the other hand, had the lowest perspiration fastness property when compared to mordanted Tencel fabric. These findings indicate that there is a clear correlation between time, temperature, and mordants used during the dyeing process and the perspiration fastness of fabric. Results are shown in tables Acidic perspiration fastness in 6 a, b and c and Alkaline perspiration fastness in table 7 a, b and c.

Table 6a. Acidic perspiration fastness of Tencel fabric on cotton fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.0	4.5	5.0
S2	2.0	4.5	4.5
S3	2.0	4.0	5.0
S4	2.0	4.5	5.0
S5	2.0	4.5	4.5
S6	2.5	4.5	5.0
S7	2.0	4.5	4.5
S8	2.0	4.5	5.0
S9	2.5	4.5	5.0

Table 6b. Acidic perspiration fastness of Tencel fabric on acrylic fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.5	5.0	4.5
S2	2.5	5.0	4.5
S3	3.0	5.0	5.0
S4	2.5	5.0	5.0
S5	2.5	4.5	5.0
S6	3.0	5.0	4.5
S7	3.0	4.5	5.0
S8	3.0	5.0	4.5
S9	3.0	5.0	5.0

Table 6c. Acidic perspiration fastness of Tencel fabric on wool fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2	4.5	5
S2	2	4	4.5
S3	2	4.5	4.5
S4	2	4.5	5
S5	2.5	4.5	4.5
S6	2.5	4.5	5
S7	3	5	4.5
S8	3	5	5
S9	2.5	5	5

Table 7a. Alkaline perspiration fastness of Tencel fabric on cotton fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.0	4.5	4.5
S2	2.5	5.0	5.0
S3	2.5	4.5	4.5
S4	2.5	4.5	5.0
S5	2.5	4.5	4.5
S6	2.5	5.0	5.0
S7	2.5	4.5	4.5
S8	2.5	4.5	5.0
S9	2.5	5.0	5.0

Table 7b. Alkaline perspiration fastness of Tencel fabric on acrylic fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.5	4.5	4.5
S2	2.0	5.0	5.0
S3	2.0	4.5	4.5
S4	2.5	4.5	5.0
S5	2.5	4.5	4.5
S6	2.5	5.0	5.0
S7	2.5	4.5	4.5
S8	3.0	4.5	5.0
S9	3.0	5.0	5.0

Table 7c. Alkaline perspiration fastness of Tencel fabric on wool fibres

Samples coding No.	Un-mordanted	Potassium aluminium sulfate	*Citrus limon*
S1	2.5	5.0	5.0
S2	2.5	4.5	5.0
S3	2.5	4.5	4.5
S4	2.0	5.0	4.5
S5	2.5	4.5	5.0
S6	3.0	5.0	5.0
S7	2.5	4.5	4.5
S8	3.0	5.0	5.0
S9	2.5	5.0	5.0

Colour *strength (K/S)*

The reflection of Unmordanted Tencel dyed fabric was evaluated by CIEL*a*b* coordinates and K/S values. The results of Colour strength(K/S) are shown in Table 8. It was observed that the colour strength value was good at higher times and temperatures. A natural neem extract was utilised to dye Tencel fabric. The colour strength of the un-mordanted Tencel fabric samples was assessed. It was observed that Tencel fabric had the best colour strength value when used at higher dyeing temperatures and times. The maximum colour strength (K/S) value was obtained from the dyed fabric at a higher dyeing temperature (65 °C) and time (75 minutes). This is because the longer time and higher temperature allowed the dye to be completely absorbed into the Tencel fabric and also increased the solubility of the dyes in water, leading to better penetration of the dyestuff into Tencel fibres and thus increasing its colour strength value.

Table 8. Colour strength (K/S) value, reflectance (%) and CIEL*a*b* values of dyed Tencel un-mordanted fabric samples

Sample code	Reflection code (%) at 400 nm	K/S at 400 nm	CIE L*a*b system		
			L	a	b
Without mordant	7.65	1.8	58.67	14.23	23.96
S1	6.4	2.90	54.10	16.20	22.20
S2	6.20	3.10	53.87	17.78	22.17
S3	6.07	3.30	53.10	17.22	21.00
S4	6.10	3.40	52.14	18.08	21.25
S5	5.74	3.60	51.03	19.56	20.98
S6	5.23	3.78	49.58	21.67	20.45
S7	4.90	3.93	46.22	23.02	20.15
S8	4.48	4.12	45.67	25.56	20.04
S9	4.30	4.20	44.07	27.01	19.99

*Grading on grey scale (Excellent-5, Good-4, Average -3, Poor-2, Very Poor-1)

Upon scrutinizing the CIE L*ab** system data, a multifaceted comparison emerges between the mordanted samples (S1 to S9) and the reference "Without Mordant" sample. First and foremost, the analysis of *L values** offers a nuanced perspective on colour lightness. Notably, the mordanted samples generally exhibit higher L* values than the "Without Mordant" sample. This suggests that mordanting imparts a characteristic lightness to the samples, rendering them visually lighter in colour compared to the untreated counterparts.

Moving on to the *values**, which signify the position along the red-green axis in the colour spectrum, we discern a distinctive trend. The mordanted samples often feature higher a* values when juxtaposed with the "Without Mordant" sample. This elevation in a* values suggests a discernible shift toward the red end of the spectrum, implying that mordanting has the effect of infusing a reddish undertone into the colouration of these samples.

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Intriguingly, a similar pattern emerges when considering the *b values**, which represent the position along the yellow-blue axis. The mordanted samples typically exhibit lower b* values in comparison to the "Without Mordant" sample. This lower b* value implies a proclivity towards bluish tones in the colouration of the mordanted samples.

The comprehensive analysis of the CIE *Lab** system data underscores the substantial impact of mordanting on the colour attributes of the samples. It manifests in the form of heightened lightness, a shift towards reddish hues along the red-green axis, and a predilection for bluish undertones along the yellow-blue axis. This intricate interplay of colour parameters elucidates the intricate role mordants play in influencing the visual perception and chromatic characteristics of textile materials.

This research used various colour fastness tests to evaluate Tencel-mordanted and un-mordanted samples. Test methods were used to evaluate fabric colour fastness according to standards for washing fastness: ISO 106 C06 (B1M), fastness to rubbing: AATCC 8, and fastness to perspiration: ISO 105 E04. The results of the colour fastness tests were compared between the mordanted and un-mordanted samples. The results showed that mordanted samples had higher fastness values than non-mordanted samples, indicating that mordanting can improve the fastness of Tencel fabrics. The dyeing time and temperature also have a significant effect on the Tencel fabric's fastness properties. The study results showed that the use of mordant had a positive effect on the colourfastness properties of Tencel fabric and that dyeing time and temperature also had a significant effect. In this experiment, Potassium aluminium sulfate and *Citrus limon* mordants were used to mordant Tencel fabric at different times and temperatures. The meta-mordanting method was used to mordant the Tencel fabric. The mordanted and un-mordanted samples were evaluated for the fastness of their colour to washing, rubbing, and perspiration using the grey scale method. The results showed that the mordanted samples had significantly better colour fastness than the non-mordanted samples, indicating a positive effect of mordanting on colour fastness. However, the performance of the non-mordanted samples was poor, and they showed significant colour fading after the tests.

It was discovered that dyeing Tencel fabric at high temperatures for an extended period improved its fastness properties significantly. Dyeing time had a significant effect on the colourfastness properties of Tencel fabric, as it is an important factor affecting the depth of colour and the degree of dye penetration. The fastness properties of Tencel fabrics improved significantly with the increase in dyeing time. The dyeing time improves the fastness property of the Tencel fabric because the longer the dyeing time, the more the dye particles can penetrate and attach to the fibres of the Tencel fabric. As a result, samples dyed for longer periods had better fastness properties than samples dyed for shorter periods. The dyeing temperature was also an important factor affecting the dyeing process. Dye absorption rate and colour depth were found to improve with the increase in dyeing temperature, which in turn improved the fastness properties of the fabric. Increasing the dyeing temperature makes the dyeing process more effective, as higher temperatures can accelerate the rate of diffusion and increase the penetration of dye particles into the Tencel fabric fibres. This is because the increased temperature results in a weakening of the electrostatic force between the Tencel fabric and the dye particles, making them easier to absorb. As a result, higher temperatures can improve dyeing performance by increasing the penetration of dye particles into Tencel fabric.

The mordanting process helps improve dye uptake and enhances the bond between the dye and the fabric. After mordanting, the Tencel fabric acquires good fastness properties because the mordanting process creates a strong bond between the dye molecules and the fibre molecules, which helps to retain the colour fastness of the fabric when exposed to various physical or chemical forces. In addition, the mordants act as stabilisers for the dye molecules, reducing their mobility and making them more resistant to the destructive forces of water, abrasion, and perspiration. In this experiment, *Citrus limon* outperformed Potassium aluminium sulfate mordant in terms of fastness properties. *Citrus limon* is acidic, with a pH level between 2 and 3. Whereas the pH level of Potassium aluminium sulfate is between 5 and 8. Because of the higher acidity of *Citrus limon* mordant, the pH difference is responsible for its increased fastness properties as compared to the Potassium aluminium sulfate mordant. The results of this experiment indicate that the pH difference is a major factor influencing the fastness properties. Overall, the results clearly show the importance of mordanting in achieving good colourfastness. Mordanting is necessary not only to improve colourfastness but also to make the dyes more resistant to the wear and tear of daily use.

CONCLUSION

Recently there has been a discernible shift towards more sustainable and eco-friendly practices in various industries, including textiles and fashion. This shift is driven by growing environmental awareness and concerns over the ecological impact of conventional synthetic dyes and chemical processes. Consequently, natural dyes and bio-mordants have garnered increasing attention as an eco-conscious alternative.

The appeal of natural dyes and bio-mordants lies in their inherent eco-friendliness. Unlike synthetic dyes, which often involve the use of toxic chemicals and generate harmful waste byproducts, natural dyes are derived from renewable sources like plants, insects, or minerals. Bio-mordants, in particular, are compounds obtained from natural materials that facilitate the binding of these natural dyes to fabric fibres. This not only reduces the environmental footprint but also eliminates the health risks associated with synthetic dye production and usage.

The current study delved into the practical application of these eco-friendly alternatives by examining the colourfastness properties of Tencel fabrics. To take this eco-friendly approach a step further, the researchers utilized neem leaves as the source of the natural dye, harnessing the rich colour potential of this plant.

In their quest to improve the colourfastness of Tencel fabric, two mordanting techniques were compared: bio-mordanting and chemical mordanting, both administered through the meta-mordanting method. This approach allowed for a comprehensive assessment of the various factors influencing colourfastness. The study found that meta-mordanting, as a whole, emerged as a highly effective method for enhancing the fabric's ability to retain its colour over time.

Significantly, bio-mordanting outperformed chemical mordanting in terms of dye uptake, indicating the superiority of bio-based solutions in this eco-conscious context. Furthermore, the study uncovered a correlation between higher temperatures and extended dyeing times, resulting in increased dye uptake, which has valuable implications for sustainably optimizing the dyeing process.

In conclusion, this research underscores the potential of bio-mordanting as a powerful and environmentally friendly tool for improving the colourfastness properties of Tencel fabric. It serves as a notable example of how sustainable practices can be seamlessly integrated into the textile industry, contributing to a more environmentally responsible and socially conscious approach to fashion and textiles.

Author Contributions

Conceptualization – Rani J, and Guru R; methodology – Rani J, and Guru R; formal analysis – Rani J, and Guru R; investigation – Rani J, and Guru R; resources – Rani J, and Guru R; writing-original draft preparation – Rani J, and Guru R; writing-review and editing – Rani J, and Guru R; visualization – Rani J, and Guru R; supervision – Rani J, and Guru R. All authors have read and agreed to the published.

Conflicts of Interest

The authors declare no conflict of interest.

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