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Enhancing Antimicrobial and Fastness Properties of Silk and Lyocell Fabric by Dyeing with *Azadirachta indica* and Mordanting with *Citrus limon* Extract

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Article

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ABSTRACT

Antimicrobial resistance presents a substantial global health challenge, prompting the exploration of innovative strategies to combat pathogenic bacteria. Within this context, considerable attention has been directed towards textile materials treated with antimicrobial agents for their potential to mitigate the spread of infectious diseases. This research sought to investigate the influence of Neem dyeing and Lemon mordanting on enhancing the innate antimicrobial properties of Silk and Lyocell fabric. Textile materials underwent mordanting exclusively with natural agents, such as citrus lemon extract, to enhance dye adherence. The dyeing process involved the use of Azadirachta indica dye obtained through aqueous boiling, applied to lyocell and silk fabrics under various parameters. The key findings revealed a significant augmentation in the antimicrobial effectiveness of lyocell and silk fabrics following Neem dyeing and Lemon mordanting. Optimized conditions, including prolonged dyeing time, elevated temperatures, and constant dye concentrations, notably improved inhibition percentages against common pathogens like Staphylococcus aureus and Klebsiella pneumoniae. Furthermore, the study assessed the washing and perspiration fastness properties of silk and lyocell fabrics in accordance with established standards. In conclusion, the integration of Neem dyeing and Lemon mordanting emerges as a promising method to significantly enhance the antimicrobial efficacy of Lyocell and silk fabrics. This approach opens avenues for the development of textiles with heightened infection control properties, particularly in sectors focused on public health and hygiene. The evaluation of fastness properties also yielded excellent results, further supporting the viability of this method in academic and practical contexts. Considering the global challenge of antimicrobial resistance, adopting such innovative strategies in textile treatment can contribute significantly to the development of effective and sustainable solutions. Future research endeavours may explore additional applications and variations of this method, ensuring its adaptability and widespread implementation in diverse settings.

KEYWORDS

silk, lyocell fabric, antimicrobial properties, Azadirachta indica, lemon, dyeing, mordanting

INTRODUCTION

The art of dying textiles is as old as civilization itself. Natural colours are thought to have been used by the peoples of the Greco-Roman periods, according to historical records. Some natural dyes evidence has been discovered in the Atharveda [1,2]. The wall painting in Ajanta was done with natural coloured materials. Additionally, developments extending into the Middle Ages show that these natural dyes were also used during this period. The natural dyes were retrieved from the ancient era for dyeing and printing the fabric. In the middle of the last century, the majority of natural dyes were extracted from plants and animals [3-5]. Synthetic dyes were first introduced in the mid-19th century, allowing for greater control of colour and a wider range of hues to choose from. Synthetic dyes are also known as coal tar dyes. For a long time, these dyes have been popular for producing bright, vivid colours that are often seen in modern fashion today [6]. Some synthetic dyes are made from petroleum-based chemicals, including toluene, anthraquinone, and naphthalene. The list of chemical dyes is extensive and includes azo dyes, acid dyes, reactive dyes, basic dyes, direct dyes, mordant dyes, and many more [7]. Synthetic dyes are popular because of their versatility, vibrant colours, and long-lasting effects. These dyes have a very small number of advantages compared to their disadvantages. Some of the synthetic dyes are banded in some regions [8]. Azo dyes, for example, are banned in some regions due to their potential carcinogenic, mutagenic, and teratogenic effects. Despite the potential health risks associated with synthetic dyes, they remain popular because of their low cost and easy availability [9].

Now that people are aware of the sustainability and environmental issues associated with the usage of chemical-based dyes [10]. That is why natural dyes are in high demand among consumers. Natural dyes have grown in popularity in recent years due to their non-toxic and biodegradable properties. They offer the same vibrant colours as their chemical-based counterparts but are considered a much more sustainable and eco-friendly alternative [11]. Many businesses have started to make the switch from synthetic dyes to natural dyes to meet the increasing consumer demand for sustainable products [12].

The introduction of contemporary methodologies like Microwave-Assisted Extraction (MAE), Supercritical Fluid Extraction (SFE), Plasma Extraction, Gamma Radiation-Assisted Extraction, and Ultraviolet (UV)-Assisted Extraction has caused a paradigm shift in the field of extraction techniques in recent years. These state-of-the-art techniques have revolutionized the extraction process by providing greater efficiency, reduced environmental impact, and improved selectivity when compared to traditional methods. Target component release is accelerated through the use of microwaves in microwave-assisted extraction, which drastically reduces extraction time and solvent usage. Supercritical Fluid Extraction is a technique that uses supercritical fluids like carbon dioxide to extract compounds with exceptional selectivity. This method operates under milder conditions, which helps to preserve the integrity of thermally sensitive compounds [17]. Plasma Extraction and Gamma Radiation-Assisted Extraction are advanced techniques that break down cellular structures, resulting in rapid and efficient extraction. These methods also have the added benefit of sterilization.

Ultraviolet-assisted extraction utilizes UV light to induce chemical reactions, which facilitates the selective release of compounds while minimizing processing time. These modern extraction techniques are a significant breakthrough in analytical chemistry and hold promise for diverse applications across pharmaceuticals, food processing, and environmental analysis. They address the growing demand for sustainable and efficient extraction processes in various industries. Supercritical Fluid Extraction, employing supercritical fluids like carbon dioxide, not only demonstrates exceptional selectivity but also operates under milder conditions, preserving the integrity of thermally sensitive compounds. Plasma Extraction and Gamma Radiation-Assisted Extraction leverage advanced technologies to break down cellular structures, providing rapid and efficient extraction with the added benefit of sterilization. Ultraviolet-assisted extraction utilizes UV light to induce chemical reactions, facilitating the selective release of compounds while minimizing processing time. These modern extraction techniques represent pivotal strides in the realm of analytical chemistry and hold promise for diverse applications across pharmaceuticals, food processing, and environmental analysis, addressing the growing demand for sustainable and efficient extraction processes in various industries [18].

Neem is a medicinal plant, and it belongs to the family Meliaceae. The scientific name of neem is *Azadirachta indica*, and it is native to the Indian subcontinent [13]. It is typically grown in hot and dry climates, making it an ideal tree for India and its neighbouring countries' environments. Neem is a fast-growing plant, and it can reach a height of up to 30 metres, making it an impressive sight in many parts of India [14]. This plant is evergreen and has a lifespan of about 200 years. The leaf shedding during the winter is an excellent source of natural fertiliser for the local soil, allowing farmers to practise sustainable agriculture in the area. The neem plant is approximately similar to the tamarind tree [15,16]. The plant produces an edible fruit that is high in nutrients and antioxidants. The traditional uses of neem plants date back to ancient times; even today, the dried leaves are put into the cupboard to protect the clothes from insects [19]. It is also put into the rice and wheat tins to protect them from insects and to keep the grain fresh. Additionally, neem is renowned for its medicinal properties and is used to treat a wide variety of ailments [20]. The neem tree has been used as medicine for thousands of years and is an essential part of traditional Indian medicine, known as Ayurveda [21]. It is not used in Ayurveda but is also used in Chinese and Unani medicines worldwide, especially in the Indian subcontinent, to prevent various diseases [22-23].

Neem trees have the most important active compound azadirachtin. Azadirachtin is a tetranortriterpenoid limonoid complex found in the seeds of the neem tree. Its compound is responsible for the toxic and antifeedant effects on insects [24]. The ethanol extract of neem leaves has an antibacterial effect on gram-positive and gram-negative bacteria [25-27]. The most populous zone, with 100% concentration on MRSA. Other active compounds found in neem trees include nimbin, nimbidin, nimbidol, sodium nimbinate, nimbolinin, gedunin, salannin, and quercetin. The leaves of the neem tree contain a variety of compounds, including nimbin, nimbanene, 6-desacetylnimbinene, nimbandiol, nimbolide, ascorbic acid, n-hexacosanol, amino acids, 7-desacetyl-7-benzoylazadiradione, 7-desacetyl-7-benzoylgedunin, 17-hydroxyazadiradione, and nimbiol [28-31]. From the fresh neem tree leaves, which contain Quercetin, ß-sitosterol, and polyphenolic flavonoids, were purified [32-33]. In this research endeavour, we delve into the examination of the antimicrobial attributes exhibited by silk and lyocell fabrics, exploring their variations across different dyeing durations and temperatures. A crucial element in this investigation is the maintenance of constant dye concentration, as our primary focus lies in discerning the specific impacts of varying dyeing time and temperature on bacterial properties under consistent dye concentration conditions. Lemon was employed as a meta-mordant during the sample preparation process. Beyond the assessment of antimicrobial properties, our study also extends to the evaluation of colourfastness properties in the treated fabrics. The rationale behind this research stems from the imperative need to enhance antimicrobial features in textiles while minimizing reliance on chemical agents that pose considerable environmental risks. The contemporary socio-environmental landscape demands a heightened commitment to sustainability, with a growing awareness of the adverse effects of chemical interventions on the earth and its ecosystems. Therefore, this research contributes to the ongoing discourse on sustainable practices in textile production, aligning with the escalating societal inclination towards eco-friendly and environmentally conscious solutions.

The novelty of this study lies in its innovative use of traditional dyeing and mordanting methods, combined with modern antimicrobial research, to develop textiles with heightened infection control properties. By optimizing parameters such as dyeing duration, temperature, and dye concentration, the research demonstrates how these factors can be tailored to enhance the fabric's ability to inhibit the growth of common pathogens like *Staphylococcus aureus* and *Klebsiella pneumoniae*. This novel approach not only offers a sustainable and eco-friendly method for treating fabrics but also opens new avenues for the development of textiles with inherent antimicrobial characteristics for diverse applications, ranging from healthcare to everyday apparel.

EXPERIMENTAL

Materials

Ready-to-dye cupro-stain lyocell and 100% silk fabric were procured for this test from Shahi Exports Pvt Ltd. The leaves of the neem (*Azadirachta indica*) plant were collected at the Mody University of Science and Technology campus in Laxmangarh, Rajasthan. The *Azadirachta indica* leaves were cleaned with water to get rid of any impurities, dried in the shade at room temperature, and then powdered in an electric grinder. The textile was mordanted using natural mordants, they are citrus lemon extract (natural). Citrus Limon was purchased from the local market of Laxmangarh. In this experiment, citrus lemon juice was used to improve the fastness property of dyed textiles.

Method and Methodology

The dried stem powder of *Azadirachta indica* was processed using an aqueous extraction method to obtain the dye. Another name for the aqueous extraction method is the boiling process. To remove the dye, 300 ml of water was poured into a beaker, and the water was boiled on a heating plate, the temperature of which was kept in the range of 60 °C to 70 °C. The dye was added to a water bath when the temperature reached 60 °C, and then the solution was heated until only 200 ml of water remained. After that, the filter paper was used to filter the boiling solution twice. The dye solution is now prepared to dye the textile in this way [34 -37].

Table 1. 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

AATCC 100 - 2019 Standard

Antimicrobial activity will be assessed according to the standard method AATCC 100. To investigate the antimicrobial activity of samples against common bacteria (S. aureus) gram-positive and (E. coli) gram-negative by using the AATCC 100 test method. A comparative study will be conducted between the leaves of the neem tree plant to find out whether the activity has high antimicrobial properties against common bacteria. The samples will be first treated with chemical and natural mordants lemon juice. The lemon mordants also had high antimicrobial properties against bacteria [38].

The reduction percentage of bacteria will be calculated along with the calculation of the number of units forming bacteria. According to the formula:

$$\text{Bacteria reduction percentage} = B - A / B * 100 \tag{1}$$

A is counting the number of bacteria forming units and B is the number of bacteria recovered from the sample after treating the sample [38].

Colour fastness assessment

The colour fastness of dyed fabric was evaluated for their washing and perspiration fastness properties according to the standards Washing fastness: ISO 106 C06:2010 (B1M) and Perspiration Fastness: ISO 105 E04. The rate for colour changes on a score from 1 (very poor) to 5 (excellent) was observed.

RESULTS AND DISCUSSION

The Silk and Lyocell fabric was dyed using an extract derived from dry *Azadirachta indica* leaves, following the guidelines outlined in Table 2. To enhance the fabric's fastness properties, Citrus limon extract was employed. Each sample was assigned a specific code corresponding to the details provided in Table 2.

Table 2. 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

Impact of Neem dyeing and lemon mordanting on the antimicrobial effectiveness of Silk fabric

The investigation into the impact of Neem dyeing and lemon mordanting on the antimicrobial effectiveness of Silk fabric revealed compelling results concerning the inhibition of *Staphylococcus aureus*. The experimental process involved subjecting silk fabric to these treatments and assessing their efficacy against this bacterial strain. The results, as depicted in the provided table, delineated the varying percentages of *Staphylococcus aureus* inhibition corresponding to different treatment conditions involving temperature, time, and dye concentration.

At the temperature of 35 °C, the treated silk fabric exhibited inhibition percentages ranging from 37.70% to 41.90% over different time intervals, spanning 40 to 75 minutes, while maintaining a constant dye concentration of 7 g. As the temperature increased to 50 °C and subsequently to 65 °C, a noticeable escalation in the inhibition of *Staphylococcus aureus* was observed. At 65 °C for 75 minutes, the silk fabric demonstrated the highest level of inhibition against *Staphylococcus aureus*, reaching a substantial percentage of 48.42%.

These findings underscored a clear correlation between higher temperatures and more extended treatment durations with amplified effectiveness in inhibiting *Staphylococcus aureus* growth on the silk fabric. This suggests that the combination of Neem dyeing and lemon mordanting, particularly at elevated temperatures and longer exposure times, significantly bolstered the fabric's ability to combat *Staphylococcus aureus*, potentially enhancing its antimicrobial properties in specific environmental or application contexts.

At a temperature of 35 °C, the treated silk fabric displayed inhibition percentages ranging from 32.92% to 45.56% over different time intervals, spanning 40 to 75 minutes, while maintaining a consistent dye concentration of 7 g. As the temperature increased to 50 °C and subsequently to 65 °C, a noticeable upward trend in the inhibition of *Klebsiella pneumoniae* was evident. Notably, at 65 °C for 75 minutes, the silk fabric exhibited the highest level of inhibition against *Klebsiella pneumoniae*, reaching a substantial percentage of 45.56%.

These findings highlighted a clear association between higher temperatures and longer treatment durations with increased effectiveness in inhibiting the growth of *Klebsiella pneumoniae* on the silk fabric. Therefore, the combined application of Neem dyeing and lemon mordanting, particularly at elevated temperatures and extended exposure times significantly bolstered the fabric's ability to combat *Klebsiella pneumoniae*. This suggests a potential enhancement of the fabric's antimicrobial properties under specific treatment conditions, offering valuable insights for applications where protection against *Klebsiella pneumoniae* is essential.

The comparison between the inhibition percentages of *Staphylococcus aureus* and *Klebsiella pneumoniae* on the silk fabric treated with Neem dyeing and lemon mordanting reveals intriguing insights into the antimicrobial effectiveness against these distinct bacterial strains.

In examining the inhibition percentages, it becomes evident that *Staphylococcus aureus* generally exhibited higher susceptibility to the treatment compared to *Klebsiella pneumoniae* across varying temperature, time, and dye concentration conditions. At lower temperatures (35 °C) and shorter durations, the inhibition percentages for *Staphylococcus aureus* consistently surpassed those of *Klebsiella pneumoniae*. However, as the temperature increased to 50 °C and further to 65 °C, both bacterial strains exhibited escalated inhibition percentages, yet *Staphylococcus aureus* consistently displayed higher susceptibility to the treatment compared to *Klebsiella pneumoniae* under identical conditions.

Specifically, at the highest temperature and duration tested (65 °C for 75 minutes), the inhibition percentages for both *Staphylococcus aureus* and *Klebsiella pneumoniae* peaked. *Staphylococcus* *aureus* exhibited an inhibition percentage of 48.42%, while *Klebsiella pneumoniae* demonstrated a slightly lower inhibition percentage of 45.56%.

Table 3. Results on the antimicrobial effectiveness of Silk fabric

Samples coding No.	Temperature (°C)	Time (min)	Dye concertation (g)	*Staphylococcus aureus* (%)	*Klebsiella pneumoniae* (%)
S1	35	40	7	37.70	33.59
S2	35	55	7	36.76	32.92
S3	35	75	7	41.90	38.79
S4	50	40	7	42.78	40.38
S5	50	55	7	42.43	40.35
S6	50	75	7	45.07	42.04
S7	65	40	7	46.27	43.08
S8	65	55	7	44.68	41.54
S9	65	75	7	48.42	45.56

Impact of Neem dyeing and lemon mordanting on the antimicrobial effectiveness of Lyocell fabric

The investigation into the antimicrobial effectiveness of Lyocell fabric treated through neem dyeing and lemon mordanting revealed compelling results regarding *Staphylococcus aureus* inhibition percentages. The experimental conditions unveiled distinct trends in inhibitory effects against *Staphylococcus aureus*. At a relatively lower temperature of 35 °C, the fabric demonstrated a gradual increase in antimicrobial efficacy with prolonged exposure times. Specifically, at 40, 55, and 75 minutes, the inhibition percentages were recorded at 34.45%, 37.78%, and 41.47%, respectively. As the temperature was raised to 50 °C and 65 °C, the fabric displayed escalated inhibition against *Staphylococcus aureus*. Under these higher temperatures, the inhibition percentages ranged from 42.23% to 47.26%. Notably, the most substantial inhibition, at 47.26%, was achieved at 65 °C for 75 minutes under a dye concentration of 7 g. These findings underscore the significant impact of temperature, duration, and dye concentration in enhancing the antimicrobial properties of Lyocell fabric via neem dyeing and lemon mordanting, particularly concerning its effectiveness against *Staphylococcus aureus*.

The examination of *Klebsiella pneumoniae* inhibition percentages on Lyocell fabric treated through neem dyeing and lemon mordanting elucidated notable findings. Throughout various experimental conditions, distinct trends in the inhibition of *Klebsiella pneumoniae* were observed. At a lower temperature of 35 °C, the fabric exhibited a progressive increase in antimicrobial effectiveness with prolonged exposure times. Specifically, at durations of 40, 55, and 75 minutes, the inhibition percentages were measured at 31.02%, 34.71%, and 36.34%, respectively. Upon elevating the temperature to 50 °C and 65 °C, the fabric demonstrated heightened inhibition against *Klebsiella pneumoniae*. Under these elevated temperatures, inhibition percentages ranged from 39.18% to 43.56%. Notably, the most significant inhibition, reaching 43.56%, was observed at 65 °C for 75 minutes under a dye concentration of 7 g. These outcomes underscore the influence of temperature, duration, and dye concentration in augmenting the antimicrobial properties of Lyocell fabric through neem dyeing and lemon mordanting, specifically regarding its effectiveness against *Klebsiella pneumoniae*.

In the evaluation of *Staphylococcus aureus* (%) and *Klebsiella pneumoniae* (%) inhibition on Lyocell fabric treated through neem dyeing and lemon mordanting, distinctive patterns in antimicrobial effectiveness against the two bacteria were evident.

For *Staphylococcus aureus*, the fabric displayed a consistent rise in inhibition percentages as temperature and duration increased. At 35 °C, the inhibition increased from 34.45% to 41.47% as the time extended from 40 to 75 minutes. Elevated temperatures of 50 °C and 65 °C further boosted inhibition percentages, reaching a range of 42.23% to 47.26%. Notably, the highest inhibition recorded was 47.26% at 65 °C for 75 minutes under a dye concentration of 7 g.

On the other hand, the inhibition of *Klebsiella pneumoniae* exhibited similar trends but with slightly lower percentages compared to *Staphylococcus aureus*. At 35 °C, the inhibition ranged from 31.02% to 36.34% with increasing time intervals from 40 to 75 minutes. Under higher temperatures of 50 °C and 65 °C, the inhibition percentages varied between 39.18% to 43.56%. The highest inhibition observed for *Klebsiella pneumoniae* was also at 65 °C for 75 minutes, recording an inhibition of 43.56% under a dye concentration of 7 g.

Comparatively, *Staphylococcus aureus* consistently exhibited higher inhibition percentages compared to *Klebsiella pneumoniae* across all experimental conditions. The highest inhibition values achieved for both bacteria were notably similar, with 47.26% for *Staphylococcus aureus* and 43.56% for *Klebsiella pneumoniae*, attained at the same conditions of 65 °C for 75 minutes with a dye concentration of 7 g.

These results indicate that while both bacteria demonstrated increased inhibition with rising temperature and duration, *Staphylococcus aureus* generally exhibited higher susceptibility to the antimicrobial effects induced by neem dyeing and lemon mordanting on the Lyocell fabric compared to *Klebsiella pneumoniae*.

Table 3. Results on the antimicrobial effectiveness of Lyocell fabric

Samples coding No.	Temperature (°C)	Time (min)	Dye concertation (g)	*Staphylococcus aureus* (%)	*Klebsiella pneumoniae* (%)
S1	35	40	7	34.45	31.02
S2	35	55	7	37.78	34.71
S3	35	75	7	41.47	36.34

Samples coding No.	Temperature (°C)	Time (min)	Dye concertation (g)	*Staphylococcus aureus* (%)	*Klebsiella pneumoniae* (%)
S4	50	40	7	42.23	39.18
S5	50	55	7	41.67	39.46
S6	50	75	7	44.08	41.88
S7	65	40	7	46.77	42.90
S8	65	55	7	45.68	42.56
S9	65	75	7	47.26	43.56

Fastness properties of Tencel fabric mordanting with Citrus limon

Washing Fastness

In this extensive investigation, the research findings underscore the pivotal role of Citrus limon mordant in significantly influencing the washing fastness property of Lyocell and silk fabrics. Beyond the mordant, the interplay of time and temperature emerged as critical factors in elevating the washing fastness of both Lyocell and silk fabrics. Notably, the washing fastness of Lyocell and silk, as evidenced in the detailed findings presented in Table 4, demonstrated remarkable improvements with the application of Citrus limon mordant. The research places a strong emphasis on the indispensable nature of mordanting Lyocell and silk fabrics to optimize their washing fastness. Citrus limon mordant exhibited exceptional washing fastness for both fabrics. The meta-mordanting process, involving carefully adjusted time and temperature parameters, yielded a significant enhancement in washing fastness for both Lyocell and silk fabrics. Remarkable outcomes were achieved not only at higher dyeing times and temperatures but also at the shortest durations and lower temperatures, showcasing the versatility of the approach for both fabric types.

Perspiration Fastness

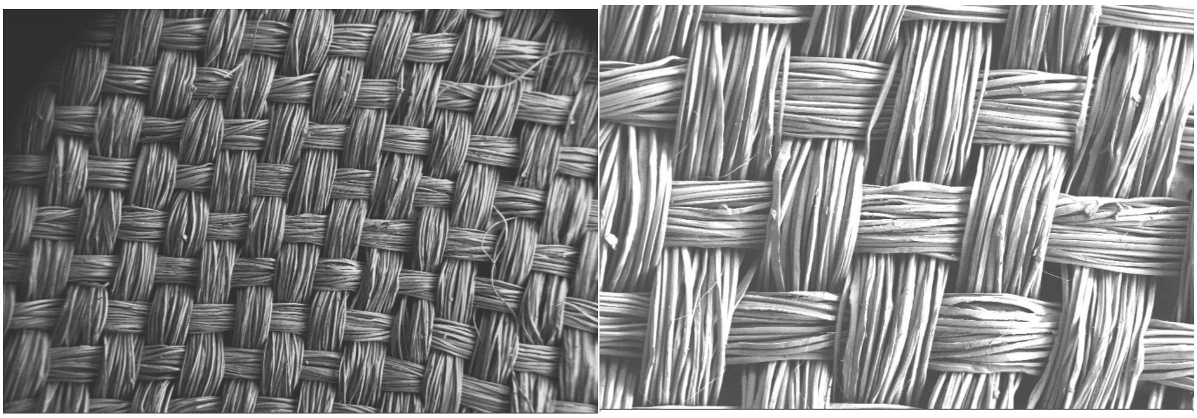
The investigation showcased a significant enhancement in the perspiration resistance of Lyocell fabric, attributing this improvement to variations in time, temperature, and the inclusion of mordants in the dyeing process. Elevated dyeing temperatures and extended dyeing durations emerged as influential factors contributing positively to the fabric's perspiration fastness. Noteworthy was the impactful boost observed in the acidic perspiration fastness properties of Lyocell fabric upon the introduction of Citrus limon mordants. Similar trends were observed when examining silk fabric, which exhibited comparable perspiration resistance to Lyocell. Notably, silk fabric demonstrated slightly higher perspiration fastness in comparison to Lyocell fabric. This implies that akin to Lyocell, the perspiration resistance of silk fabric is affected by factors such as time, temperature, and the use of mordants during the dyeing process. Results are shown in Table 4.

Table 4. Fastness properties of Tencel fabric mordanting with Citrus limon

Samples coding No.	Washing Fastness Lyocell Fabric	Washing Fastness Silk Fabric	Perspiration Fastness Lyocell Fabric	Perspiration Fastness Silk Fabric
S1	4	4.5	4.5	5
S2	4.5	5	4.5	4.5
S3	4.5	4.5	4	5
S4	4.5	5	4.5	5
S5	5	5	4.5	4.5
S6	5	5	4.5	5
S7	5	5	4.5	4.5
S8	5	5	4.5	5
S9	5	5	4.5	5

FeSem Images

The SEM images (Figures 1 to 4) depict the microscopic details of silk and lyocell fabric samples dyed with Azadirachta indica and mordanted with lemon juice. Observations reveal notable differences in surface texture, fiber diameters, particle shape, and external morphology between the treated and untreated samples. In the mordant-treated samples, both silk and lyocell fabrics exhibit smoother surfaces, more uniform fiber diameters, and particles with regular shapes compared to the untreated counterparts. These findings suggest that the mordanting process, facilitated by lemon juice, enhances the fabric's structural integrity and surface properties. While the chemical composition alterations are not directly visible in the SEM images, the observed differences likely stem from interactions between the mordant and the fabric, leading to improved dye uptake and fixation. Further analysis may provide insights into the crystalline structure and material orientation within the treated fabrics, shedding light on the microstructural changes induced by the mordanting process.

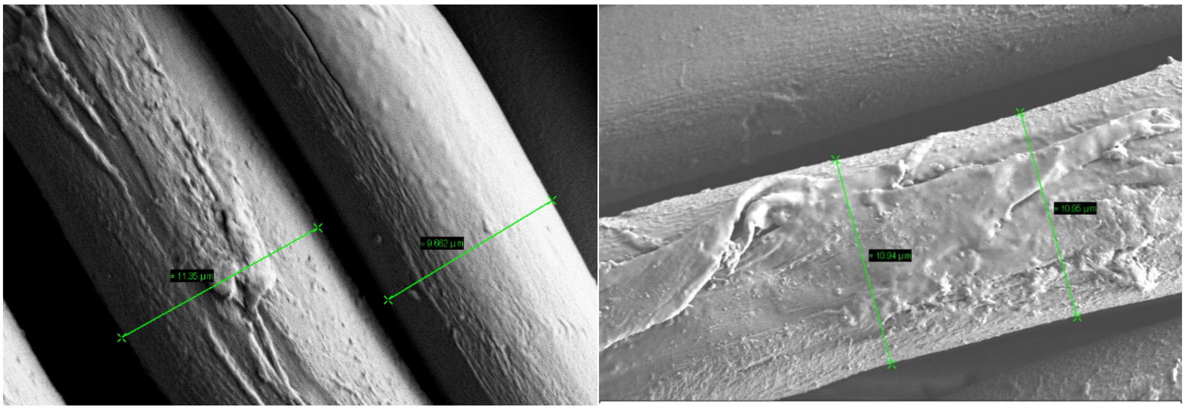


(a) (b)

Figure 1. FeSem images of silk fabric without mordanting and with mordanting

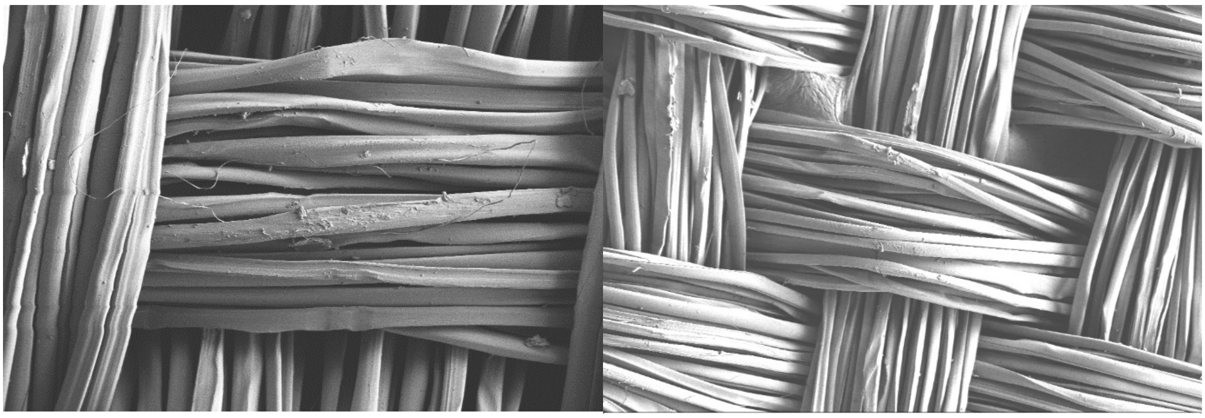
(a) (b)

Figure 2. FeSem images of silk fabric without mordanting and with mordanting



(a) (b)

Figure 3. FeSem images of Lyocell fabric without mordanting and with mordanting



(a) (b)

Figure 4. FeSem images of Lyocell fabric without mordanting and with mordanting

Effects of different parameters on antimicrobial property

The parameters of dyeing, including time, temperature, and dye concentration, play significant roles in influencing the antimicrobial effectiveness against *Staphylococcus aureus* and *Klebsiella pneumoniae* when treating fabrics like Lyocell through neem dyeing and lemon mordanting.

The duration of the dyeing process has a noticeable impact on the inhibition of both *Staphylococcus aureus* and *Klebsiella pneumoniae*. Increasing the dyeing time generally led to enhanced antimicrobial properties. For instance, with longer durations, both bacteria showed higher inhibition percentages across various temperatures and dye concentrations. This suggests that prolonged exposure during the dyeing process likely enhances the antimicrobial effectiveness of the fabric against these pathogens.

Temperature variations during the dyeing process significantly affected the antimicrobial activity against *Staphylococcus aureus* and *Klebsiella pneumoniae*. Higher temperatures, such as 50 °C and 65 °C, resulted in increased inhibition percentages for both bacteria compared to lower temperatures like 35 °C. The temperature rise appears to positively influence the fabric's antimicrobial properties, indicating that elevated temperatures potentially aid in better incorporation or activation of antimicrobial agents from neem dyeing and lemon mordanting.

Altering the concentration of the dye used during the treatment also affected the inhibition percentages against *Staphylococcus aureus* and *Klebsiella pneumoniae*. While maintaining other conditions constant, varying dye concentrations influenced the fabric's antimicrobial efficacy. Generally, higher concentrations of the dye solution resulted in increased inhibition percentages for both bacteria. This suggests that a higher dye concentration potentially leads to more significant antimicrobial activity on the fabric against these pathogens.

The parameters involved in dyeing, including time, temperature, and dye concentration, collectively impact the antimicrobial effectiveness of fabrics treated through neem dyeing and lemon mordanting against *Staphylococcus aureus* and *Klebsiella pneumoniae*. Longer dyeing durations, elevated temperatures, and higher dye concentrations generally correlated with improved antimicrobial properties, showcasing greater inhibition percentages against these bacterial strains on the treated fabric. Adjusting these parameters during the dyeing process could be crucial in tailoring fabrics with enhanced antimicrobial characteristics against specific pathogens.

The process of dyeing fabric involves a complex interaction between dyes, mordants, and fabric fibres. Achieving the desired colour fastness and durability is crucial, and this is influenced by the chemical reactions and bonding between these elements. Mordants act as agents to facilitate the fixation of dyes onto the fabric fibres. Understanding these interactions is essential in creating textiles with vibrant and long-lasting colours.

CONCLUSION

The investigation into Neem dyeing and Lemon mordanting on the antimicrobial effectiveness of Silk and Lyocell fabric revealed promising findings regarding its potential as an antimicrobial agent against pathogens like *Staphylococcus aureus* and *Klebsiella pneumoniae*. The findings revealed that the application of Neem dyeing and lemon mordanting techniques to silk and lyocell fabric resulted in notable antimicrobial properties against both *Staphylococcus aureus* and *Klebsiella pneumoniae*. The variations in temperature, time, and dye concentration influenced the antimicrobial effectiveness of the treated fabric against these bacterial strains. *Staphylococcus aureus* exhibited higher susceptibility to the treated silk and Lyocell fabric compared to *Klebsiella pneumoniae* across most experimental conditions. Although both bacteria showed increased inhibition with alterations in parameters, *Staphylococcus aureus* consistently displayed higher inhibition percentages. The study identified specific optimal conditions for achieving maximum antimicrobial effectiveness. These conditions typically involved higher temperatures, longer dyeing durations, and elevated dye concentrations, resulting in the most substantial inhibition percentages against both bacteria. The research suggests that the incorporation of neem dyeing and lemon mordanting could serve as a potential method to enhance the antimicrobial properties of textile materials, particularly Lyocell fabric, contributing to their potential use in applications requiring antimicrobial functionalities. This process, influenced by various parameters, showcases potential applications in textile industries seeking to develop fabrics with enhanced antimicrobial characteristics for diverse applications ranging from healthcare to everyday apparel. Further research and optimization of these parameters can lead to the development of more effective antimicrobial textile treatments. This comprehensive investigation sheds light on the pivotal factors influencing the washing and perspiration fastness of Lyocell and silk fabrics. The utilization of Citrus limon mordant has proven instrumental in significantly improving the washing fastness of both fabrics, highlighting its versatile efficacy across diverse dyeing conditions. The meta-mordanting process, coupled with nuanced adjustments in time and temperature parameters, showcased remarkable outcomes, underlining the indispensable nature of mordanting for optimizing fabric performance. Moreover, the study underscores the dynamic interplay of time and temperature in enhancing the perspiration resistance of Lyocell fabric, with extended dyeing durations and elevated temperatures positively influencing these properties. The introduction of Citrus limon mordants further amplified the acidic perspiration fastness of Lyocell fabric, contributing to its overall durability. Comparable trends observed in silk fabric emphasize the generalizability of these findings across different fabric types.

These insights into the intricate relationships between mordants, time, temperature, and fabric properties offer valuable guidance for textile practitioners and researchers. The study's implications extend beyond the laboratory, providing a roadmap for the strategic optimization of washing and perspiration fastness in textile manufacturing processes. As the textile industry seeks sustainable and performance-driven solutions, the knowledge gleaned from this research can pave the way for innovations that elevate the quality and durability of Lyocell and silk fabrics, contributing to advancements in both material science and textile technology.

Author Contributions

Conceptualization – Rani J, Guru R, and Panigrahi S; 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, Guru R, and Panigrahi S; writing-review and editing – Rani J, Guru R, and Panigrahi S; visualization – Rani J, and Guru R; supervision – Rani J, Guru R, and Panigrahi S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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