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FROM FOREST TO FABRIC: NATURAL DYEING WITH TEAK WOOD EXTRACT (*Tectona Grandis*) ON TRADITIONAL YARNS

ISMADI* AND SARTONO, DEDY

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ABSTRACT

This study evaluates the potential of teak wood extract (*Tectona grandis*) as a natural dye for traditional woven yarns by comparing the effectiveness of different fixation techniques in enhancing color retention and stability. A spectrophotometric analysis was conducted to measure lightness (L^*), red-green shift (a^*), and yellow-blue shift (b^*). Four fixatives - Aluminum Sulphate ($Al_2(SO_4)_3$), Natrium Bicarbonate ($NaHCO_3$), Calcium Carbonate ($CaCO_3$), and Ferro Sulphate ($FeSO_4$)—were tested to assess their impact on color transformation. The results indicate that Ferro Sulphate induced the most intense color transformation, producing deeper and darker hues, while Aluminum Sulphate yielded the most uniform and stable coloration. Calcium Carbonate enhanced lightness, whereas Natrium Bicarbonate resulted in moderate color absorption. These findings confirm the viability of teak wood extract as a sustainable alternative to synthetic dyes, supporting eco-friendly textile dyeing practices. Furthermore, this study provides scientific insights into fixation techniques, offering practical applications for both artisans and the textile industry.

KEYWORDS

Natural dye; Teak wood extract; Color fastness; Sustainability; Fixation techniques.

INTRODUCTION

Natural dyeing is regaining interest due to its sustainability and eco-friendliness. The textile industry significantly contributes to global water pollution, with synthetic dyes harming ecosystems and human health [1-3]. Synthetic dyes contain toxic chemicals that are difficult to degrade, leading to long-term environmental damage. As industries seek greener alternatives, natural dyes present an effective solution. Among them, teak wood extract (*Tectona grandis*) stands out for its rich color potential and application in traditional yarn dyeing.

Natural dyes have been used for centuries, derived from plant materials such as leaves, bark, flowers, and roots. Unlike synthetic dyes, they offer biodegradable and non-toxic alternatives, making them more suitable for sustainable textile production [4-5]. For instance, mango leaf extract has been explored as a natural dye source, particularly in batik fabric dyeing, using after-mordanting techniques to enhance color absorption and fastness, contributing to the green textile industry [6]. However, challenges remain in achieving color consistency and fastness, which depend on dye sources and fixation techniques. Additionally, the efficiency of natural dyes varies based on fiber type, dyeing conditions, and

mordanting agents, making further research essential.

Despite its potential, teak wood extract remains underexplored in the textile industry. Few studies have analyzed its effectiveness, leaving gaps in understanding its dyeing properties and fixation techniques [7-8]. Previous research on plant-based dyes has demonstrated stable and vibrant colors, yet teak wood's full potential remains unexamined [4-5] [9]. Unlike commonly used plant-based dyes such as indigo or madder, teak wood extract contains unique tannins and flavonoids that influence its dyeing behavior.

A critical aspect missing from existing research is the comparison of different fixation methods in maintaining teak wood extract's color stability. Understanding how various fixatives interact with teak dyes can optimize its application in textiles [10]. Fixatives, such as aluminum sulfate and ferrous sulfate, play a crucial role in bonding dye molecules to fibers, influencing shade intensity and longevity. The development of effective fixation techniques could enhance color retention and broaden the commercial use of teak wood extract in textile dyeing.

However, despite the growing interest in natural dyeing techniques, research on the application of teak wood extract remains limited [7]. Prior studies

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have predominantly focused on widely known plant-based dyes such as indigo, madder, and turmeric, leaving the potential of teak wood extract underexplored [11]. Additionally, research on mango seed extract (*Mangifera indica* L.) has demonstrated its viability as a sustainable alternative for batik dyeing [12], further highlighting the importance of exploring underutilized natural dye sources such as teak wood extract. Several studies have explored the potential of plant-based dyes, such as clove leaves (*Syzygium aromaticum* L.), in batik production [13], but the application of teak wood extract remains underexplored. Furthermore, most research in this area lacks comprehensive comparisons of fixation techniques that affect color stability and intensity [14-21]. Recent studies on plant-based dyes, such as mango leaf extract, have shown that after-mordanting can significantly improve color retention in traditional batik fabric, highlighting the importance of selecting appropriate fixatives in natural dye applications [6]. While some studies suggest that certain metal-based mordants enhance dye bonding, there is little consensus on which fixation method provides the most consistent and sustainable results for teak wood extract [22-25]. These gaps indicate the need for a systematic evaluation of teak wood extract dyeing and the impact of different fixatives on its color properties.

Therefore, this study aims to evaluate the stability and effectiveness of teak wood extract dyeing using different fixatives, comparing their impact on lightness retention and color transformation through spectrophotometric analysis. Unlike prior research on general plant-based dyes, this study specifically examines teak wood extract in combination with multiple fixatives, providing a comparative analysis of their effects on color retention and vibrancy.

By demonstrating the viability of teak wood extract as a natural dye, this study supports the shift toward environmentally friendly textile production [26]. Furthermore, by exploring its application on various textile fibers, this research could open new opportunities for the integration of natural dyes in modern fashion and home textiles.

MATERIALS AND METHOD

This study used an experimental design to evaluate the natural dyeing strength of teak wood extract (*Tectona grandis*) on traditional woven yarns. The research was carried out in several stages, including material preparation, the coloring process, and color analysis using a spectrophotometer. Each fixation technique was tested to determine its effectiveness in maintaining the resulting color [27-28].

The materials used in this study included teak wood extract (*Tectona grandis*), obtained through an

extraction process using water solvents, and traditional woven yarns made from natural fibers such as cotton or silk. The fixation materials consisted of Aluminum Sulphate ($\text{Al}_2(\text{SO}_4)_3$), Calcium Carbonate (CaCO_3), Ferro Sulphate (FeSO_4), and Natrium Bicarbonate (NaHCO_3). The tools used included a spectrophotometer for color analysis, an analytical scale for material measurement, a stainless-steel dyeing pot, a thermometer for temperature control, and a stirring device to ensure uniform dye distribution.

For the preparation of the teak extract, 2 kg of dried teak wood powder was boiled in 500 ml of water for 2 hours to extract the color compounds. For the preparation of the teak extract, 2 kg of dried teak wood powder was boiled in 500 ml of water for 2 hours to extract the color compounds. Similar to the extraction of clove leaf dye (*Syzygium aromaticum* L.) for batik production [13], this study employed water-based extraction of teak wood powder to obtain natural dye components (see Figure 1). The solution was then filtered to separate the solid residues. The solution was then filtered to separate the solid residues. The woven yarns were pre-washed to remove dirt and oil that might interfere with the dyeing process. Afterward, the yarns were soaked in a fixation solution for 30 minutes to enhance color absorption [29].

The fixation solution was prepared by dissolving 30 g of Aluminum Sulphate ($\text{Al}_2(\text{SO}_4)_3$), 20 g of Calcium Carbonate (CaCO_3), 28–30 g of Ferro Sulphate (FeSO_4), or 25 g of Natrium Bicarbonate (NaHCO_3) into 2 liters of clean water. These concentrations ensured a standardized comparison of the effectiveness of each fixative.

The dyeing process involved immersing the pre-treated yarns into a teak wood extract solution at 60°C for 60 minutes with constant stirring to ensure even color absorption [30-31]. After the dyeing process, the yarns were rinsed with cold water to remove excess unbound dye.





In addition to pre-mordanting, after-mordanting techniques were also considered to improve color fixation and durability, as suggested in previous studies on plant-based dyes such as mango leaf extract [12]. Research has shown that after-mordanting enhances dye-fiber bonding, leading to improved fastness properties [6].

To assess the effectiveness of fixation, the dyed yarns were subjected to spectrophotometric analysis to measure the values of L^* (lightness), a^* (red-green component), and b^* (yellow-blue component). The color difference between undyed and dyed yarns was calculated using the ΔE^*_{ab} formula to determine the effectiveness of dyeing [32].



Figure 1. Teak wood and its powder; (a) Teak Wood (*Tectona grandis*), (b) Teak wood powder.

Table 1. Visual Results of Yarn Coloring at the Final Fixation Stage.

Coloring Materials	Fixation Materials	Fixation Techniques	Visual Yarn after Dyeing
Teak Wood Extract	Aluminum Sulphate ($\text{Al}_2(\text{SO}_4)_3$)	End	
	Calcium Carbonate (CaCO_3)	End	
	Ferrous Sulphate (FeSO_4)	End	
	Sodium Bicarbonate (NaHCO_3)	End	

The data obtained from spectrophotometric analysis were statistically analyzed to determine significant differences between the fixation techniques used. This analysis was performed using ANOVA to test hypotheses and draw conclusions regarding the effectiveness of teak wood extract as a natural dye [34] [35].

RESULTS AND DISCUSSION

Result

This section presents the results of the study in a structured manner to ensure clarity and facilitate comparison. The findings are organized into three main parts: (1) Visual analysis of the dyed yarns to provide an initial qualitative assessment of color variations; (2) Spectrophotometric analysis to quantify lightness (L^*), red-green shift (a^*), yellow-blue shift (b^*), and total color difference (ΔE^*ab); and (3) Statistical validation using ANOVA to determine the significance of the observed differences between fixation techniques.

To focus on the most relevant outcomes, this study presents only the final fixation stage (End Stage) while maintaining all four fixation materials: Aluminum Sulphate ($\text{Al}_2(\text{SO}_4)_3$), Calcium Carbonate (CaCO_3), Ferro Sulphate (FeSO_4), and Sodium Bicarbonate (NaHCO_3). This approach ensures a more precise comparison of each fixative's impact on color stability and intensity.

Table 1 presents the visual appearance of yarns after the final fixation stage for each fixative. This provides an initial observation of how different fixation agents influence color outcomes before moving to quantitative analysis.

These visual results serve as a preliminary comparison before moving to the spectrophotometric and statistical analysis, which will provide deeper insights into color variation and stability.

Spectrophotometry Analysis

Spectrophotometric analysis was conducted to evaluate the color differences at the final stage of fixation. The parameters measured included L^* (lightness), a^* (red-green), b^* (yellow-blue), and ΔE^*ab (total color difference). To quantitatively compare the impact of each fixation technique, Table 2 provides a summary of spectrophotometric measurements, including lightness (L^*), red-green shift (a^*), yellow-blue shift (b^*), and total color difference (ΔE^*ab).

Interpretation of Spectrophotometric Results

Aluminum Sulphate ($\text{Al}_2(\text{SO}_4)_3$) maintains moderate lightness (L^*), ensuring stable color absorption. The relatively lower ΔE^*ab values indicate higher color uniformity, making it effective for achieving consistent dyeing results.

Calcium Carbonate (CaCO_3) retains the highest L^* values, meaning it produces brighter shades.

Table 2. Comparative L^* , a^* , b^* , and ΔE^*ab Values for All Fixation Techniques (Final Stage).

Fixation Materials	Fixation Techniques	Test to	Yarn Color Difference Test Value			
			L *	a*	b*	ΔE*ab
White Thread has not been dyed		0	106.63	1.04	-3.35	0
Aluminum Sulphate (Al ₂ (SO ₄) ₃)	End	1	46.04	15.57	-3.72	62.31
		2	45.43	4.98	31.72	70.65
		3	45.72	21.63	-9.18	64.56
Calcium Carbonate (CaCO ₃)	End	1	54.56	9.11	-7.05	52.82
		2	57.04	10.86	-13.45	51.55
		3	56.6	18.67	-23.93	56.9
Ferro Sulphate (FeSO ₄)	End	1	28.31	-13.09	54.15	98.18
		2	20.82	23.77	-41.64	96.68
		3	16.91	13.43	-26.12	93.39
Natrium Bicarbonate (NaHCO ₃)	End	1	39.09	20.42	-18.96	71.3
		2	39.24	17.71	-18.28	71
		3	45.14	0.97	13.67	63.8

However, its higher ΔE^*ab suggests a greater risk of color inconsistency across the fabric.

Ferro Sulphate ($FeSO_4$) causes the most significant reduction in L^* values, leading to darker and deeper color absorption. It also produces the highest ΔE^*ab , indicating the most intense transformation among the fixatives.

Natrium Bicarbonate ($NaHCO_3$) exhibits moderate color absorption, with L^* values higher than Ferro Sulphate but lower than Calcium Carbonate. Its ΔE^*ab values suggest a less dramatic color shift, making it suitable for producing softer, more natural hues.

Comparison of Fixation Techniques at the Final Stage

To evaluate the effectiveness of different fixation techniques, this section compares their impact on lightness retention (L^*) and total color difference (ΔE^*ab) at the final stage. The analysis provides insight into how each fixative alters the color properties of teak wood extract on yarns.

To provide a clearer comparison, Figure 2 and Figure 3 illustrate how each fixation technique influences lightness (L^*) and total color difference (ΔE^*ab) at the final stage.

- Figure 2 presents the retention (L^*), showing which fixative produces the brightest lightest or darkest results. A higher L^* value corresponds to greater retention lightness, while a lower L^* value reflects deeper color absorption and a darker appearance.
- Figure 3 visualizes the total color difference (ΔE^*ab), allowing for a clearer comparison of how significantly each fixative alters the original yarn color. A higher ΔE^*ab value indicates a greater transformation, with Ferro Sulphate exhibiting the

most pronounced shifts, while Aluminum Sulphate and Natrium Bicarbonate result in more moderate changes.

The line chart in Figure 2 demonstrates how each fixative affects the lightness or darkness of the dyed yarns. Among the tested fixatives, Calcium Carbonate exhibited the highest L^* values, indicating that it produced the brightest lightest results. In contrast, Ferro Sulphate resulted in the lowest L^* values, meaning it led to darker shades and deeper color absorption. These differences suggest that Calcium Carbonate retains more lightness, while Ferro Sulphate enhances deeper color penetration.

The heatmap in Figure 3 visually represents the degree of color change across different fixatives. A higher ΔE^*ab value signifies more significant alterations, with Ferro Sulphate producing the most dramatic shifts. This aligns with its role in deepening color intensity. Meanwhile, Aluminum Sulphate and Natrium Bicarbonate result in more moderate ΔE^*ab values, suggesting that they provide more stable and uniform color retention.

These findings indicate that Ferro Sulphate is most effective for achieving deep and intense hues, whereas Calcium Carbonate is preferable for lighter, brighter tones. Meanwhile, Aluminum Sulphate and Natrium Bicarbonate offer a balance between stability and moderate color changes, making them suitable for applications requiring controlled color variations.

Statistical Analysis (ANOVA Test Results)

To validate whether the observed color differences between fixation techniques are statistically significant, an ANOVA test was conducted on ΔE^*ab values. Table 3 summarizes the results, highlighting variations in color transformation caused by different fixatives.

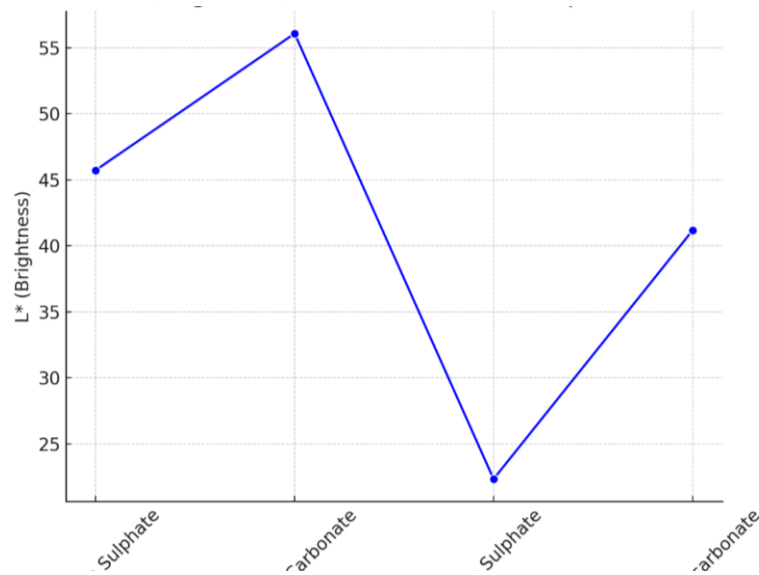


Figure 2. Line Chart of L* (lightness) Across Fixation Techniques at the Final Stage.

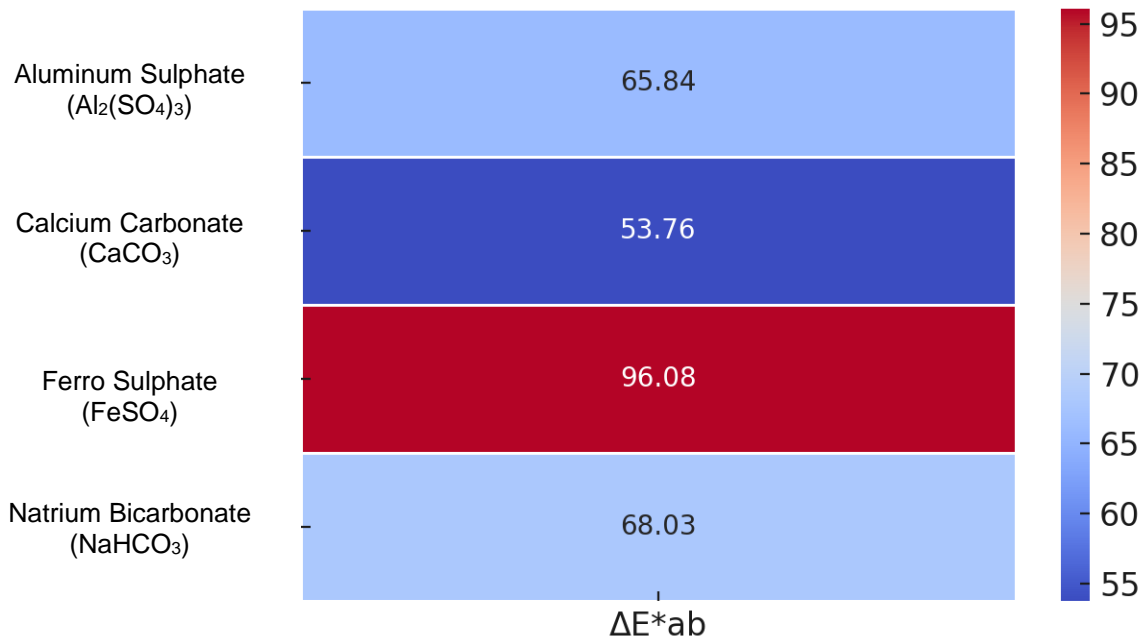


Figure 3. Heatmap of ΔE^*ab (Color Difference) Across Fixation Techniques at the Final Stage.

Table 3. ANOVA Test Results for ΔE^*ab Across Fixation Techniques.

Source of Variation	Sum of Squares (SS)	Degree of Freedom (df)	Mean Square (MS)	F-value
Between Groups	0.00	3	0.00	75.97
Within Groups	100.93	8	12.62	-
Total	100.93	11	-	-

The results indicate a significant difference in color transformation among fixation techniques ($F = 75.97$, $p < 0.05$), confirming that the choice of fixative substantially affects the final color outcome. Post-hoc analysis suggests that Ferro Sulphate differs significantly from the other fixatives, reinforcing its strong impact on color transformation.

Implications for Thread Dyeing Instruction in Craft Education

The findings of this study hold strong relevance for teaching thread dyeing in Craft Education, particularly in courses related to textile dyeing techniques, textile crafts, and sustainability in crafts. Utilizing teak wood extract as a natural dye not only enriches color

exploration in textile crafts but also provides scientific insights into the interaction between fixative agents and textile fibers.

In textile craft courses, students can study how fixatives such as Aluminum Sulphate, Calcium Carbonate, Ferro Sulphate, and Natrium Bicarbonate influence lightness levels (L^*), red-green shifts (a^*), yellow-blue shifts (b^*), and total color difference (ΔE^*ab). Through laboratory-based or studio-based experiments, they can evaluate how specific fixatives produce more stable or intense colors, offering valuable insights for future artisans and textile designers.

In the context of batik and traditional woven fabric dyeing, understanding fixation techniques is highly beneficial for students looking to develop textile works using natural dyes. Many batik and weaving artisans still rely on trial-and-error approaches to determine the best fixative, making this study a scientific reference for students interested in applying natural dyeing methods more precisely. By understanding the varying effects of fixatives, they can confidently choose the appropriate techniques to achieve durable and uniform colors.

Beyond technical aspects, this research also has implications for craft education focused on sustainability. With growing awareness of environmentally friendly craft practices, the use of natural dyes such as teak wood extract serves as an alternative to synthetic dyes, which have negative environmental impacts. In craft courses emphasizing innovation and ecology, students can develop dyeing approaches that utilize local resources more sustainably while preserving traditional values in textile craft practices.

Integrating these research findings into the Craft Education curriculum can provide students with a deeper learning experience in natural dyeing exploration. By combining scientific, technical, and sustainability aspects, students not only gain theoretical knowledge of the dyeing process but also develop the ability to apply it in innovative craft practices relevant to today's creative industries.

Discussion

The results of this study indicate that different fixation techniques significantly influence the final color outcomes of teak wood-dyed yarns. The spectrophotometric analysis shows that Ferro Sulphate leads to the most pronounced color transformation, producing the deepest and darkest shades, while Calcium Carbonate results in higher lightness retention. The statistical analysis further supports these findings, confirming that the differences observed among fixation techniques are significant ($F = 75.97$, $p < 0.05$).

These findings align with previous studies on natural dyeing processes, which suggest that different fixatives interact uniquely with tannins and other color

compounds in natural dyes. For instance, research by [36] also found that metal-based fixatives, such as Ferro Sulphate, intensify color depth by enhancing mordant-dye interactions. Similarly, studies by [15], [37] and [38] demonstrated that iron-based fixatives produce darker and richer hues due to their strong affinity with tannin-rich natural dyes. Previous studies on clove leaf dye (*Syzygium aromaticum* L.) suggested its potential for batik production due to its stable color properties [13]. In contrast, teak wood extract exhibited different characteristics, particularly in its reaction with fixation agents such as Ferro Sulphate and Calcium Carbonate. In contrast, alkaline fixatives like Calcium Carbonate tend to produce lighter hues by shifting the pH balance of the dyeing solution, as reported by [39-41].

A similar trend has been observed in natural dyeing using mango leaf extract, where after-mordanting techniques were reported to improve color fastness by enhancing the dye-fiber interaction [6]. Studies on mango leaf extract indicate that applying mordants after the dyeing process allows for better absorption and fixation of tannin-rich compounds, resulting in enhanced dye stability and resistance to fading. However, our findings show that teak wood extract exhibits stronger pre-mordanting effects, particularly when combined with Ferro Sulphate, which produces deeper and more intense hues. The comparison suggests that while after-mordanting techniques may improve color longevity, pre-mordanting with specific fixatives can enhance color intensity and shade depth in tannin-based dyes. This distinction highlights the importance of selecting appropriate mordanting methods depending on the desired color outcome and durability.

However, differences were observed when compared with the findings of: [17] [40] [42] [43], who noted that aluminum-based fixatives often lead to brighter yet more stable colors. In our study, Aluminum Sulphate showed moderate lightness retention but did not enhance color vibrancy as much as Calcium Carbonate. This variation may be attributed to differences in dye composition and fiber characteristics. Additionally, research by [44] and [45] suggested that Sodium Bicarbonate can create a more uniform color distribution, yet our findings indicate that it resulted in moderate color absorption with less dramatic color shifts.

Moreover, the results indicate that Aluminum Sulphate and Natrium Bicarbonate offer moderate color retention, making them viable options for achieving balanced color intensity. These findings are valuable for textile artisans and industries seeking sustainable dyeing techniques, as they provide insights into how fixative selection can optimize both color vibrancy and stability. Previous research on mango seed extract (*Mangifera indica* L.) has highlighted its effectiveness as an eco-friendly dye for batik, particularly in improving color retention and

fastness [12]. Compared to mango seed extract, teak wood extract interacts differently with fixation agents such as Ferro Sulphate and Aluminum Sulphate, leading to variations in color intensity and lightness retention.

Theoretical, Pedagogical, and Curriculum Implications

These findings have significant implications for both the textile industry and traditional dyeing practices. The strong effect of Ferro Sulphate in deepening color saturation confirms its potential for applications requiring rich, dark tones, making it particularly relevant for artisans producing handcrafted textiles with long-lasting, intense hues. Conversely, Calcium Carbonate's ability to retain lightness offers an alternative for industries aiming to achieve lighter, more uniform hues, particularly in eco-friendly fabric production [46]. These findings reinforce the importance of natural dyeing techniques in reducing dependence on synthetic chemicals while maintaining high-quality color results.

From a theoretical perspective, this study deepens the understanding of color fixation by demonstrating the varying effects of different fixatives on dye stability and transformation. The strong affinity of Ferro Sulphate with tannin-based dyes aligns with existing theories on metal-based mordants, which enhance dye-fiber interactions and darken color tones. Meanwhile, the brightening effect of Calcium Carbonate supports the principle that alkaline conditions shift color balance by altering dye solubility and fiber binding [38] [47-50]. These findings reinforce established models of natural dye chemistry while expanding knowledge on the role of fixatives in color uniformity and longevity.

In the context of textile dyeing education, these findings serve as valuable instructional resources, particularly in laboratory-based learning, where students can directly observe the impact of different fixatives on color outcomes. By integrating these results into practical coursework, students gain hands-on experience in natural dyeing processes, enabling them to analyze spectrophotometric data and refine their dyeing techniques based on scientific principles. This approach enhances problem-based learning (PBL) by encouraging experimentation with different mordants and critical evaluation of dye-fiber interactions [51-55]. Furthermore, integrating sustainability-focused dyeing techniques in craft education fosters an awareness of eco-friendly material applications, preparing students for responsible design practices.

With the growing emphasis on sustainability in the craft and textile industries, this study underscores the importance of integrating natural dyeing methods into the curriculum of Craft Education programs. Incorporating spectrophotometric analysis into coursework bridges the gap between traditional

craftsmanship and scientific methodologies, providing students with both artistic and technical expertise [56] [57]. Courses such as Natural Dyeing Techniques, Textile Sustainability, and Applied Color Chemistry can offer a balanced perspective between creative expression and environmental responsibility. This integration ensures that graduates not only understand historical and contemporary natural dyeing methods but also develop the skills necessary to innovate within the textile industry using sustainable materials and processes.

Strengths and Limitations of the Study

This study provides a comprehensive evaluation of teak wood extract as a natural dye in combination with different fixatives, offering valuable insights into color development and stability. The integration of spectrophotometric analysis and statistical validation strengthens the reliability of the findings, making them applicable to both academic research and industrial applications. Additionally, this study aligns with the global movement toward sustainable textile production by promoting the use of natural dyes as eco-friendly alternatives to synthetic colorants [7], [58-60].

However, several limitations must be acknowledged. Since the experiments were conducted under controlled laboratory conditions, the findings may not fully capture real-world textile dyeing challenges, where variables such as temperature, humidity, and water pH can significantly impact color retention [61-64]. Furthermore, the study did not assess the long-term durability of the dyed yarns, particularly in terms of color fastness to washing, light, and rubbing, which are crucial for textile industry applications [14], [17] [37], [65]. Additionally, this research focused exclusively on teak wood extract; future studies should investigate other plant-based dye sources to determine whether similar fixation trends apply across different natural dyes.

Future research could build on these findings by exploring the molecular interactions between teak wood extract and fixatives using advanced spectroscopic techniques [66-68]. Such investigations would provide a deeper understanding of the chemical bonding mechanisms involved in natural dye fixation, enhancing the practical applications of these techniques in commercial textile production.

By advancing knowledge on fixation techniques and their impact on color stability, this study contributes to the development of eco-friendly dyeing methods, paving the way for more sustainable and scientifically informed textile practices.

CONCLUSION

This study examined the effects of different fixation materials on the final color outcomes of teak wood-dyed yarns. The results indicate that Ferro Sulphate

produced the most intense color transformation, yielding darker and richer hues due to its strong interaction with tannin-based dye compounds. In contrast, Calcium Carbonate resulted in higher lightness retention, making it a suitable fixative for achieving lighter shades. Aluminum Sulphate and Natrium Bicarbonate demonstrated moderate effects, balancing color retention and absorption, thus providing stable but less dramatic color variations.

The statistical analysis ($F = 75.97$, $p < 0.05$) confirmed significant differences among the fixation techniques, reinforcing the critical role of fixatives in determining final color properties. These findings align with previous research on natural dye fixation while also expanding the understanding of teak wood extract as a dye source, particularly in relation to its interaction with different mordants.

From a practical perspective, these results offer valuable insights for textile artisans, natural dye researchers, and eco-friendly dyeing industries in selecting optimal fixation methods to achieve specific color effects. Additionally, the study highlights the potential of natural dyes as sustainable alternatives to synthetic dyes, supporting global initiatives for environmentally responsible textile production.

For future research, long-term durability tests on color fastness to washing, light exposure, and rubbing should be conducted to evaluate the practicality of teak wood extract in commercial applications. Additionally, expanding the study to other natural dye sources and fiber types could further validate the findings. Advanced spectroscopic analysis of molecular interactions in natural dye fixation would also enhance the scientific understanding and industrial applicability of this process.

Overall, this study contributes to the growing body of knowledge on natural dyeing techniques, providing a scientific foundation for optimizing the use of teak wood extract in sustainable textile production.

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OPTIMIZING THE DYEABILITY OF POLYESTER FABRICS WITH DISPERSE DYES USING AN ORTHOGONAL DESIGN

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ABSTRACT

This study explores the combined effects of dye concentration, dyeing time, and acid concentration on the color strength (K/S value) of polyester fabrics dyed with Disperse Scarlet GS200 (DSG). The Taguchi L25 orthogonal array design was employed to optimize the dyeing process while reducing experimental effort and material usage. Color strength and fastness properties were evaluated through spectrophotometric measurements and analyzed using Minitab statistical software. Among the three variables, dyeing time was found to have the most significant influence on the K/S values, followed by dye concentration, whereas acid concentration had a relatively minor effect. These results highlight the importance of controlling processing time to achieve optimal coloration. In addition to color strength analysis, FTIR spectroscopy was used to examine the interaction mechanisms between DSG dyes and polyester fibers. The results suggested the presence of physical bonding, such as Van der Waals forces or hydrogen bonding. Vapor permeability tests further supported the dye–fiber interaction and fabric surface changes after dyeing. Overall, the findings contribute to improving dyeing efficiency and fabric quality while supporting environmentally conscious practices in textile manufacturing by identifying optimal dyeing conditions with reduced chemical input and energy usage.

KEYWORDS

Polyester Fabric; Disperse Dyes (DSG); Taguchi Method; Orthogonal Design; Color Strength (K/S).

INTRODUCTION

The textile dyeing industry has long been recognized as a major contributor to water pollution, having significant negative impacts on both freshwater ecosystems and human health. One of the primary environmental concerns is the discharge of toxic wastewater, which often contains hazardous substances such as heavy metals, synthetic dyes, bleaching agents, and other chemical auxiliaries [1] [2]. These pollutants, when released untreated or insufficiently treated into the environment, can cause serious ecological damage. The presence of these chemicals in water bodies disrupts aquatic ecosystems by altering pH levels, reducing oxygen content, and interfering with sunlight penetration, which collectively impact biodiversity and disturb aquatic food chains. Furthermore, exposure to such contaminated water can lead to various health risks for humans, particularly for communities relying on nearby water sources for daily use.

In addition to its toxicity, the dyeing process in the textile sector is extremely water-intensive. Large

volumes of freshwater are consumed throughout different stages of dyeing—from fiber pre-treatment to dye fixation and washing—resulting in significant water depletion, particularly in regions already experiencing water stress [3]. Alarming, it is estimated that the textile industry is responsible for nearly 20% of global industrial wastewater, making it one of the leading industrial polluters of freshwater resources [4]. The widespread discharge of untreated dye effluent into rivers and oceans not only pollutes natural water systems but also leads to long-term degradation of aquatic habitats [5].

The environmental strain caused by textile dyeing has been further intensified by the rapid expansion of the global fashion industry, especially the rise of fast fashion. This trend emphasizes short production cycles, frequent collection updates, and low-cost garments, leading to higher textile output and, consequently, increased water usage and pollution [6]. As a result, the demand for dyeing processes has grown substantially, exacerbating water contamination problems and placing immense pressure on freshwater sources. This situation is

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particularly problematic in low- and middle-income countries, where a majority of textile manufacturing takes place and where water treatment infrastructure is often inadequate or lacking [7].

Among synthetic fibers, polyester has become one of the most widely used materials in the global textile market due to its outstanding physical properties. These include high tensile strength, excellent durability, low moisture absorbency, and resistance to shrinkage, stretching, and abrasion [8] [9]. These characteristics make polyester ideal for a wide range of applications, from fashion and sportswear to home textiles. However, dyeing polyester fabrics is more complex compared to natural fibers. Polyester's hydrophobic and tightly packed molecular structure presents challenges in achieving desirable color depth and consistent washing fastness [10-12]. As a result, the optimization of dyeing conditions is crucial for achieving both aesthetic quality and long-lasting performance.

Improving dyeing efficiency requires careful control over several key parameters, including dye concentration, temperature, time, pH level, and the use of dispersing or leveling agents. Adjusting these variables can lead to better dye penetration, increased color strength, and more efficient dye fixation on the fiber surface. Such optimization not only enhances fabric quality but also contributes to reducing water, energy, and chemical usage during production, which is vital for addressing environmental concerns [13] [14]. Typically, the dyeing process for polyester with disperse dyes is carried out in closed dyeing systems at temperatures around 130°C to promote dye diffusion into the fiber matrix [15] [16]. However, the effectiveness of this process can vary depending on multiple factors, such as the concentration of the dye, the dyeing duration, and the pH of the dye bath [17].

To systematically evaluate the influence of these parameters, the Taguchi method was applied in this study using an L25 orthogonal array. This approach allowed for the simultaneous analysis of three critical variables—dye concentration, dyeing time, and acid concentration—and their effects on two key outcomes: color strength (measured in K/S values) and washing fastness [18] [19]. The Taguchi method is a robust statistical optimization tool that minimizes the number of experimental trials while maximizing the amount of information gathered. By varying multiple factors simultaneously and analyzing their interactions, it helps researchers identify the most significant parameters affecting a process and determine optimal conditions with fewer resources [20] [21]. The goal of this study is to optimize the dyeing process for polyester fabrics using Disperse Scarlet GS200 (DSG) dye to achieve maximum color strength and improved fastness properties under efficient dyeing conditions. Through the Taguchi method, the study aims to reduce unnecessary

chemical usage, minimize energy and water consumption, and lower the volume of harmful effluents released into the environment. By identifying the optimal combinations of dyeing parameters, manufacturers can achieve better dye fixation and improved fabric performance with minimal ecological footprint. In addition to experimental results on color strength and fastness, the study also integrates FTIR spectral analysis and vapor permeability testing to better understand the interaction mechanisms between DSG dye and polyester fibers. These techniques provide insight into how the dye physically associates with the fabric—likely through Van der Waals forces or hydrogen bonding—rather than through covalent chemical bonding. This contributes to the overall understanding of dye–fiber interactions and supports the optimization process.

Ultimately, the research contributes to the broader objective of sustainable textile manufacturing by combining scientific experimentation with statistical analysis. The findings can be applied not only to DSG dyes but also serve as a model for optimizing disperse dyeing processes more generally. By refining operational parameters and reducing chemical waste, this study supports more environmentally responsible practices in the dyeing industry, balancing production efficiency with ecological sustainability.

EXPERIMENTS

Materials

The work used 100% polyester plain woven fabric with a specific weight of 183.5 g/m², which was provided by Truong Thinh Ltd. Co (Vietnam). The fabrics were pretreated by desizing and scouring to remove any impurities, ensuring the consistency of dyeing results. Disperse Scarlet GS200 (DSG) dyes were purchased from Qingdao Sanhuan Colorchem (China), a widely used disperse dye for polyester fabrics, was chosen due to its strong color properties. DSG is a type of disperse dye commonly used for dyeing synthetic fibers, particularly polyester. It is known for its good color fastness properties, vibrant shades of red, high compatibility, and safety. DSG dyes are designed to be insoluble in water and are typically applied using heat, which allows the dye to penetrate the fibers. It is primarily used in dyeing processes such as pad dyeing, batch dyeing, and continuous dyeing. The dye is usually applied in a dispersion, which is then heated to fix the color to the fabric.

Various dye concentrations were prepared in distilled water. The dyeing solution was acidified using acetic acid (CH₃COOH) to adjust pH, which plays a critical role to optimize dye penetration and fixation. Different concentrations of CH₃COOH were tested to determine its effect on dyeing performance. Levelling agent (namely, Albenol - dra) was used to assist in dyeing and fixation.

Experimental design

Polyester fabric was dyed using exhaust method. Samples were dyed at varying DSG concentrations with the optimized process parameters including time, temperature, and pH value. Six different dye concentrations were tested. Dyeing times were varied to investigate the time effect on color strength and washing fastness. A constant temperature of 130°C was maintained for all dyeing experiments to ensure adequate dye penetration into hydrophobic polyester fibers.

Taguchi Orthogonal Array Design (L25) was selected to assess the effect of the three key factors (dye concentration, dyeing time, and pH value) at five levels each. This statistical design reduced the total number of experimental trials while allowing for interaction effects to be observed, including 1) Factor A (dye concentration), 2) Factor B (acid concentration), 3) Factor C (dyeing time). The combination of these variables was systematically varied based on the orthogonal array design (Taguchi method) to optimize the dyeing process through color strength as well as color intensity. Minitab 2010 was used as a powerful statistical software in fields such as manufacturing, engineering, and research for data analysis and process optimization. To optimize the product quality, Minitab supports the Taguchi method.

The color strength (K/S) of each dyed sample was measured using a UV-visible spectrophotometer (X-rite) to evaluate the reflectance. Higher K/S values indicate greater color depth and intensity.

The results in this research were also clarified which the analysis of Fourier-transform infrared spectroscopy (FTIR) and air permeability test were used to determine the bonding mechanism and the structural change in treated samples compared to untreated samples. The washing fastness of dyed

polyester fabrics was examined according to ISO 105-C06 standard. Each dyed sample was subjected to a washing test, and the color changes were quantified by measuring the color difference (ΔE) between the original and post-wash samples.

RESULTS AND DISCUSSION

Maximum light absorption of dyed polyester fabric at various dye concentrations

The CIELab diagram visualizes color characteristics of polyester fabrics dyed with different dye concentrations (red dye) (Figure 1). Black dots suggests that all dye concentrations place color firmly in the red quadrant. Obviously, the red intensity increases with higher dye concentrations, resulting in color consistency and strong red hue dominance across samples.

The K/S values, indicating color strength, were plotted across the visible spectrum (400–700 nm) for polyester fabrics dyed with DSG dyes at different concentrations (1% to 6%) as shown in Figure 2. Each curve reveals a distinct absorption peak, with the highest absorption observed around 550–600 nm, corresponding to the red region of the visible spectrum. This suggests that DSG dyes mainly absorb red light, producing complementary colors on the fabric. As dye concentration increases from 1% to 5%, K/S values also rise significantly, showing enhanced dye uptake and stronger coloration. This trend highlights the role of concentration in improving color depth. However, beyond 3%, the rate of increase in K/S values slows, suggesting that dye absorption becomes less efficient. The fabric surface may approach saturation, meaning additional dye molecules no longer contribute proportionally to color

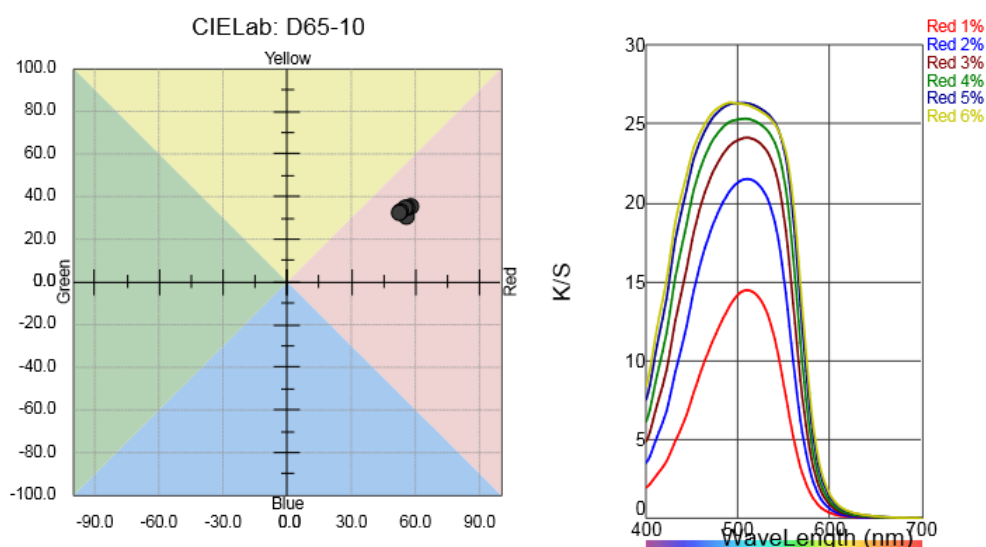


Figure 1. Maximum light absorption and CIELab diagram of polyester samples dyed with 1%, 2%, 3%, 4%, 5%, and 6% DSG dyes in the wavelength range of 400 to 700 nm.

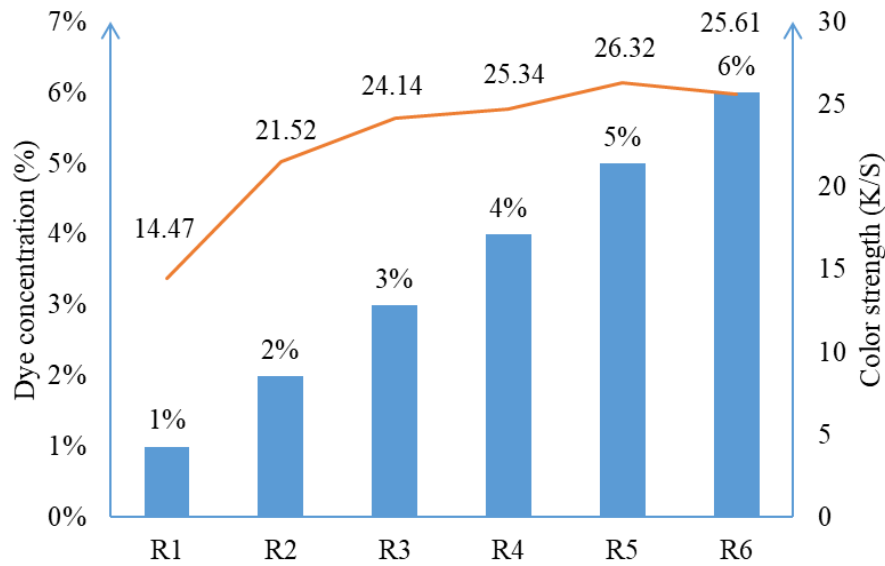


Figure 2. K/S values of polyester fabrics dyed with 1, 2, 3, 4, 5 and 6 % of DSG dyes.

Table 1. Levels of three parameters including dye concentration (X_1), acid concentration (X_2) and dyeing time (X_3) on polyester fabrics dyed with disperse dyes.

Level	X_1 dye concentration, %	X_2 acid concentration, %	X_3 dyeing time, min
1	2.0	0.00	20
2	3.0	0.75	35
3	4.0	1.50	50
4	5.0	2.25	65
5	6.0	3.00	80

strength. This behavior indicates a threshold concentration - around 3% - after which higher dye levels result in minimal K/S improvement. Recognizing this helps optimize dye usage, avoiding waste while maintaining high color quality in polyester dyeing processes.

Simultaneous effects of dye concentration, dyeing time, and acid concentration

The Taguchi orthogonal array design was essential in analyzing and quantifying the effects of key dyeing parameters on polyester fabric performance using DSG disperse dyes. This method allowed for the evaluation of three main variables—dye concentration (X_1), acid concentration (X_2), and dyeing time (X_3)—as shown in Table 1. It efficiently revealed both individual and interaction effects among these factors, helping to understand their impact on dye uptake and color strength. A major advantage of the Taguchi approach is its ability to minimize the number of required experiments while still delivering meaningful statistical insights. Unlike traditional factorial designs, this method saves time

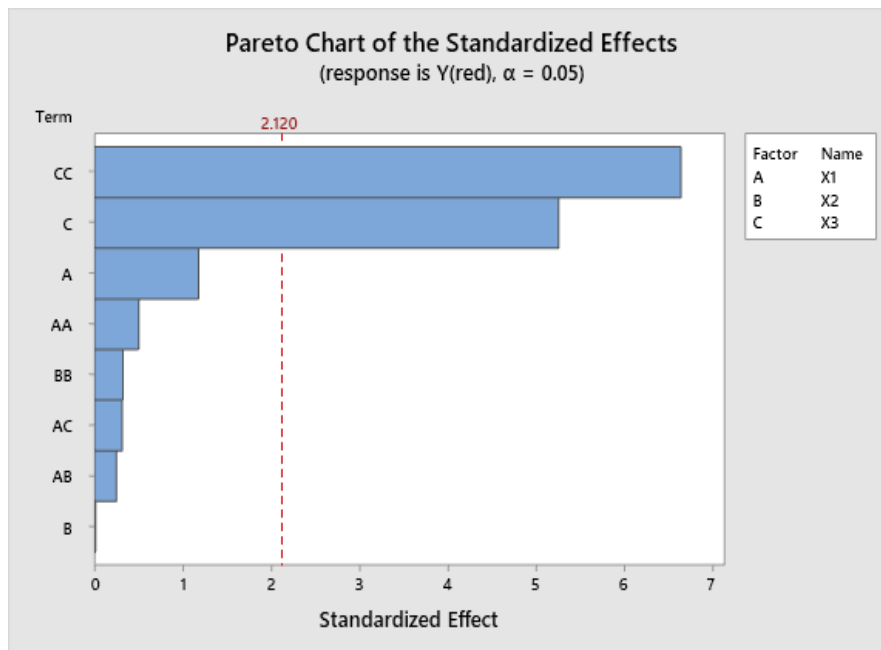
and resources without compromising data quality. Despite fewer trials, it provides strong evidence of how each factor and their combinations influence dyeing results. Furthermore, the study showed that this optimization strategy supports more efficient and reproducible dyeing processes. It enables better control over variables, leading to enhanced dyeability, improved fabric appearance, and more sustainable textile production practices.

The results in Table 2 demonstrate that all parameters contributed to the K/S value of polyester fabrics, with X_3 having the most significant effect at **32.31%**, followed by X_1 at **1.26%**, and X_2 at **0.02%**.

Figure 3 shows a Pareto Chart of Standardized Effects for the K/S value (i.e., $Y(\text{red})$) with a significance level of $\alpha = 0.05$. The chart illustrates the relative importance of factors A (X_1 : dye concentration), B (X_2 : acid concentration), and C (X_3 : dyeing time), along with their interactions (e.g., AB, AC). The threshold for statistical significance was marked at 2.120. Factors CC and C have the largest effects, extending farthest to the right and indicating that dyeing time (C) has the greatest impact on the K/S value. Factor A (dye concentration) also exceeds

Table 2. Experimental matrix results on the effects of dye concentration, acid concentration, and dyeing time on the K/S value using Taguchi L25 method.

Source	DF	Seq SS	Contrib. (%)	Adj SS	Adj MS	F-Value	P-Value
Model	8	328.400	85.50	328.400	41.050	11.80	0.000
Linear	3	128.998	33.59	101.944	33.981	9.76	0.001
X_1	1	4.836	1.26	4.836	4.836	1.39	0.256
X_2	1	0.068	0.02	0.001	0.001	0.00	0.990
X_3	1	124.094	32.31	96.164	96.164	27.63	0.000
Square	3	199.016	51.82	159.123	53.041	15.24	0.000
$X_1 * X_1$	1	0.880	0.23	0.880	0.880	0.25	0.622
$X_2 * X_2$	1	1.071	0.28	0.363	0.363	0.10	0.751
$X_3 * X_3$	1	197.064	51.31	153.541	153.541	44.12	0.000
2-way interaction	2	0.386	0.10	0.386	0.193	0.06	0.946
$X_1 * X_2$	1	0.040	0.01	0.219	0.219	0.06	0.805
$X_1 * X_3$	1	0.346	0.09	0.346	0.346	0.10	0.757
Error	16	55.681	14.50	55.681	3.480		
Total	24	384.082	100.00				


Figure 3. Pareto Chart of Standardized Effects for K/S value (Y(red), $\alpha = 0.05$).

the significance threshold, showing a notable effect. Other terms (AA, BB, AC, AB, and B) fall below this threshold and are not statistically significant. Overall, dyeing time is the most influential factor on the K/S value, followed by dye concentration (A), while acid concentration (B) has minimal impact. The regression model of the K/S value in coded variable form is described by the following equation.

$$Y(\text{red}) = 5.39 + 0.93X_1 - 0.30X_2 + 11.56X_3 - 0.11(X_1)^2 + 0.08(X_2)^2 - 1.71(X_3)^2 - 0.07X_1X_2 + 0.08X_1X_3 \quad (1)$$

where $R = 85.5\%$.

This equation affirms that Y(red) is the dependent variable, while X_1 , X_2 , and X_3 are the independent variables (predictors). It demonstrates that as the independent variables X_1 , and X_3 increase, the dependent variable Y(red) also tends to increase (i.e.,

positive coefficients). In contrast, as the independent variable X_2 increases, the dependent variable Y (red) tends to decrease (i.e., negative coefficient)

Figure 4 determined the normal distribution of the simultaneous effects of dye concentration, acid concentration, and dyeing time on the color strength of the fabric. From these results, it is shown that the points close to the diagonal line represent the influence of dye concentration, acid concentration, and time on the K/S color strength according to a normal distribution. This variation in color strength is due to random factors, with no abnormalities. The downward curve on the left side of the graph and the upward curve on the right indicate a left-skewed distribution pattern. The density of points on the lower left side near the diagonal suggests that the effects of dye concentration, acid concentration, and dyeing time on fabric color strength follow a right-skewed distribution.

It can be explained that there is an optimal dyeing time after which the K/S value stabilizes. Although extended dyeing times can enhance dye penetration, they may not always lead to significantly better results. Increasing dye concentration consistently raised the K/S value across all experiments. However, beyond a certain concentration, further increases in K/S plateaued, indicating a saturation point where additional dye no longer contributes significantly to deeper colors. Finally, acid concentration is another critical factor, particularly in influencing the dyeing process and colorfastness. While higher acid concentrations improve dye fixation, excessively high acid levels may cause fabric degradation or other undesirable effects. After optimizing the dyeing parameters, the following dyeing and washing recipe was proposed as DSG (5%), CH_3COOH (0.75%), levelling agent (1.0 g/l), and washing agent (1.0 g/l).

Physical and chemical properties of dyed fabrics with DSG dyes

To gain a deeper understanding of the chemical bonding interaction mechanism between DSG dyes and polyester fibers under optimized dyeing conditions—as determined using the Taguchi orthogonal array design outlined earlier—an in-depth analysis of the FTIR spectra provides critical insights. The spectral differences between untreated and dyed polyester samples help elucidate several important aspects of how DSG dyes interact with the fiber's chemical structure during the dyeing process (Figure 5). The FTIR baseline spectra, corresponding to the untreated polyester sample (SP0), primarily display characteristic peaks that reflect the inherent chemical composition of polyester. These include strong absorption bands associated with the carbonyl ($\text{C}=\text{O}$) stretching vibrations, methyl and methylene ($\text{C}-\text{H}$) stretching, and other typical functional groups found in the polymer backbone. In this untreated state, the

fiber remains chemically unmodified, with no influence from dye molecules or processing conditions. Although DSG dyes are not capable of forming covalent bonds with the polyester substrate, they can still establish physical interactions, primarily via Van der Waals forces and possibly hydrogen bonding. These non-covalent interactions, though weaker than covalent bonds, can still cause observable modifications in the FTIR spectra. Such modifications may include slight shifts in the position of absorption bands and changes in peak intensities due to alterations in the molecular environment of the functional groups involved.

In the dyed samples, specifically SP4 and SP6, the FTIR spectra exhibit notable differences when compared to the untreated sample. One of the most prominent observations is the increased intensity of peaks in regions corresponding to hydroxyl ($\text{O}-\text{H}$) and carbonyl ($\text{C}=\text{O}$) stretching vibrations. This suggests a greater degree of dye-fiber interaction, possibly due to enhanced dye uptake, stronger hydrogen bonding, or dye aggregation at the fiber surface. These changes in spectral features support the hypothesis that optimized dyeing conditions facilitate more

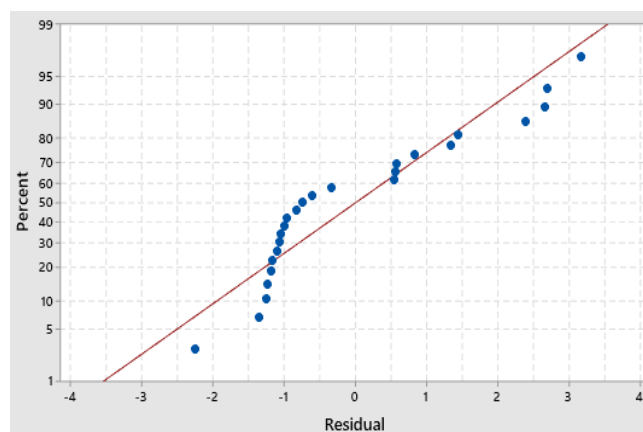


Figure 4. Normal probability of simultaneous effects between dye concentration (A), acid concentration (B) and dyeing time (C) for dyed polyester fabrics on K/S value.

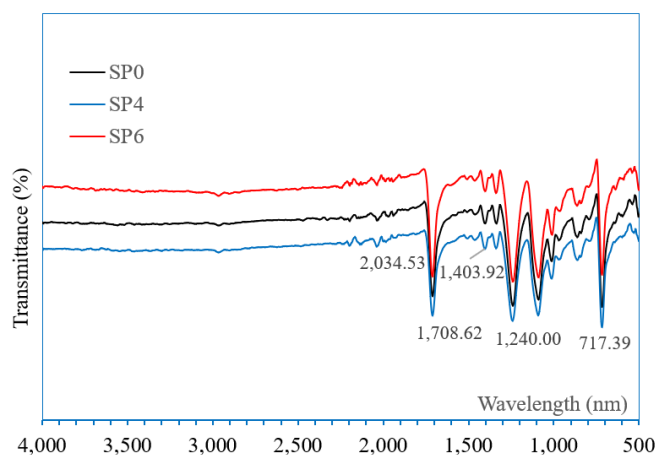


Figure 5. FTIR spectra of polyester fabrics dyed with 0% (SP0), 4% (SP4) and 6% of DSG dyes.

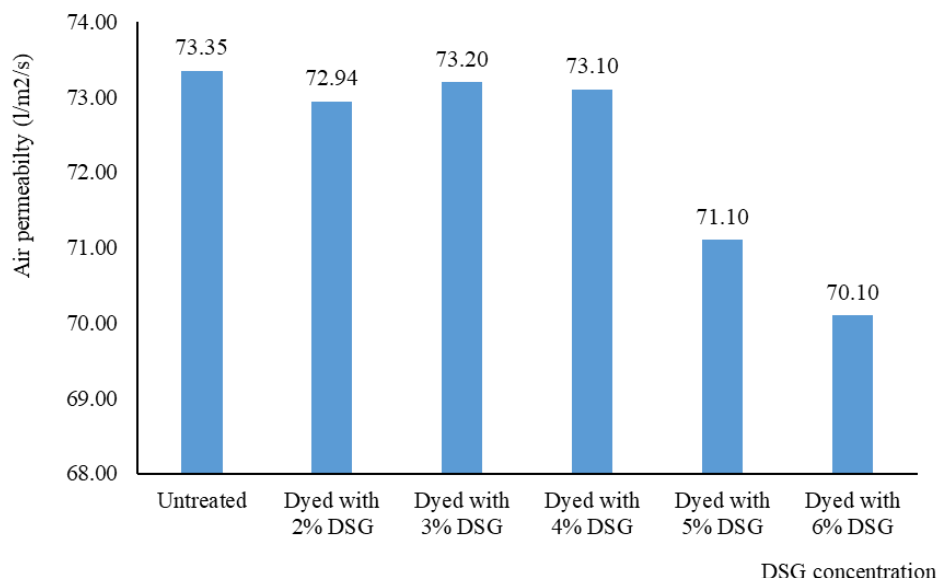


Figure 6. Breathability of polyester fabrics dyed with 0, 2, 3, 4, 5 and 6% of DSG dyes (20 cm² of test area, and 100 Pa of pressure).

effective dye penetration and binding, even in the absence of chemical bonding. Additionally, subtle shifts in peak positions, especially within the fingerprint region (1,500–700 cm⁻¹), may indicate minor structural rearrangements in the polyester polymer. These could arise from changes in intermolecular forces or variations in polymer crystallinity as a result of the dyeing process. In some cases, new absorption bands may appear, pointing to localized interactions between the dye molecules and specific sites on the fiber. Overall, the FTIR analysis highlights the significance of physical interactions in the dyeing mechanism and provides evidence of how the optimized parameters enhance these effects, leading to improved dyeability of polyester fabrics with DSG disperse dyes.

Figure 6 illustrates the air permeability results of polyester fabrics dyed with varying concentrations (0%, 2%, 3%, 4%, 5%, and 6%) of Disperse Scarlet GS200 (DSG) under standardized dyeing conditions at 130°C for 60 minutes. The data reveal a slight, gradual decline in air permeability as the dye concentration increases, suggesting that the accumulation of DSG dyes on the fabric surface slightly affects the pore structure of the polyester. This subtle reduction in air flow is expected due to the presence of dye molecules that may partially settle into or near the micro-pores of the fabric during high-temperature dyeing. Despite this minor decrease, the overall breathability of the dyed polyester fabrics remained largely unaffected, as the air permeability values did not deviate significantly from those of the undyed control samples. This indicates that the dyeing process with DSG does not substantially hinder the airflow or comfort properties of the fabric. The azo functional groups and hydrophobic aromatic structures present in DSG dyes may slightly interfere

with air exchange, but their effect is minimal and not detrimental to end-use applications. Therefore, the maintained air permeability of dyed fabrics reinforces their suitability for commercial textile products, particularly in apparel where breathability is essential for wearer comfort. This finding adds value to the practical applicability of DSG dyes in polyester processing.

CONCLUSION

This study successfully optimized the dyeing process for polyester fabrics using Disperse Scarlet GS200 (DSG) by employing the Taguchi L25 orthogonal array method, which allows for efficient evaluation of multiple parameters with minimal experimental trials. Through systematic analysis, it was determined that among the three investigated factors—dye concentration, dyeing time, and acid concentration—dyeing time had the most significant influence on color strength (K/S values). Dye concentration also contributed notably to the overall dyeing outcome, while acid concentration exhibited only a minor effect. These findings highlight the importance of accurately controlling key variables in order to maximize dye uptake and color depth. The optimized conditions derived from the Taguchi approach led to considerable improvements in dyeing efficiency, enabling stronger coloration with potentially lower resource usage. Furthermore, the presence and interaction of DSG dyes within the polyester fiber matrix were confirmed by Fourier-transform infrared (FTIR) spectral analysis, which revealed specific shifts and changes in absorption bands that support the occurrence of dye-fiber interactions. In addition, vapor permeability (breathability) tests indicated that the dyeing process had minimal impact on the comfort properties of the fabric. Overall, this research

offers a scientifically grounded and environmentally conscious strategy for enhancing the polyester dyeing process, paving the way for more sustainable and cost-effective practices in textile manufacturing.

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INFLUENCE OF DYEING TECHNOLOGICAL CONDITIONS ON THE COLOR CHARACTERISTICS AND ANTIBACTERIAL PROPERTIES OF COTTON-POLYESTER TEXTILES

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ABSTRACT

The article is devoted to establishing the influence of an intensifier on color characteristics, color fastness indicators, and antibacterial properties of textile materials. The proposed method confirms the expediency of using the selected intensifier when dyeing cotton-polyester textile materials. Concentrations of the intensifier during their treatment were determined. The influence of the intensifier on the color intensity and its resistance to physicochemical factors was established. The antibacterial activity of the treated samples was confirmed.

KEYWORDS

Intensifier; Triclosan; Dyeing; Cotton-polyester Textile; Antibacterial Properties.

INTRODUCTION

In recent years, the textile industry has been widely developing the direction of functionalization of textile materials to provide new properties [1–5]. A special case is antibacterial functionalization. The intensive development of society has led to the mass spread of viruses and microorganisms, causing numerous epidemics and pandemics, such as smallpox, cholera, tuberculosis, yellow fever, Spanish flu and coronavirus [6].

The main and most promising direction of expanding the range and improving the properties of textile materials of various compositions is not so much the development of new types of chemicals for the production of textile fibers, but the modification of existing fibers and finished textile materials in order to give them new properties [1–9].

A fairly wide range of natural and synthetic compounds have antimicrobial activity, but many of them are dangerous for humans and animals. Therefore, only some chemical compounds can be recommended for practical use as antiseptic preparations [8, 9].

The main method of imparting antibacterial properties to textile materials is the use of antimicrobial preparations (biocides).

The requirements for biocides used for application to textile materials are as follows:

- effectiveness of action against the most common microorganisms at a minimum concentration of the antibacterial substance and a maximum duration of its action;
- non-toxicity to the human body of the biocide concentrations used;
- absence of color and odor;
- low cost of the biocide, which should not lead to a significant increase in the price of the finished product with antibacterial properties;
- no deterioration in the physical, mechanical, hygienic and other properties of the textile material due to its modification with biocidal substances;
- combination with the preparations used for processing materials and textile auxiliaries used in the production process of the material;
- light resistance, weather resistance.

Providing antibacterial properties to textile materials protects the surface of the material from the action of various microorganisms, as well as protects the human body from the action of pathogenic microflora that gets on textile materials. Otherwise, it is necessary to create conditions for a preventive attack by the textile material on pathogenic bacteria and fungi to prevent their action on the object of protection.

An effective way to protect humans from viruses and harmful microorganisms is the use of protective textile

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materials. Consumers have focused directly on medical products, and as a result, the use of textiles in the field of medicine, hygiene and health care has become much wider due to new antimicrobial drugs, functional fibers, new chemical coatings and technologies. Textile materials treated with triclosan could be a good alternative in obtaining antibacterial characteristics of textile products for medical applications, such as face masks, medical gowns and wound dressings [7, 10]. Thus, it is advisable to investigate the possibility of using triclosan as an intensifier in the dyeing of textile.

There are known studies on the improvement of various antimicrobial components in the creation of textile materials for human protection, including quaternary ammonium compounds, triclosan, polybiguanides, N-galamines and metals such as silver and antimicrobial substances of natural origin [7, 10-12]. There are various methods for obtaining antimicrobial efficiency of the fabric.

Triclosan or 2,4,4'-trichloro-2'-hydroxydiphenyl ether is a product that has antimicrobial activity and, by the mechanism of action on microorganisms, inhibits their growth, affecting the biosynthesis of fatty acids by stopping the biosynthesis of lipids through a reaction with amino acid residues of the enzymatically active center inside the membrane [12]. One of the methods for obtaining antibacterial textile material is the treatment of bleached cotton fabric with triclosan. Subsequently, it was subjected to the action of polycarboxylic acids, namely: 1,2,3,4-butanetetracarboxylic and citric acids as crosslinking agents to prolong antibacterial properties. The surface of the fibers treated with 1,2,3,4-butanetetracarboxylic acid had a larger crosslinking area, and the surface of the fabrics, under the action of citric acid, had a larger number of deformations due to mechanical and chemical effects after 50 washes [13].

In work [14], the effectiveness of using triclosan in imparting antibacterial properties to viscose-polyester nonwovens was proven. The purpose is achieved by using the method of dry spraying of synthesized polylactide microspheres containing triclosan onto nonwovens. The triclosan content in the microspheres ranged from 4.65 to 4.95 wt.%. The antibacterial nonwovens were investigated using the inhibition zone measurement method, having antibacterial properties against Gram (+) – *Staphylococcus aureus* and Gram (-) – *Klebsiella pneumoniae* from 4 to 9 mm [14].

Cotton-polyester textile materials have been widely used in many industries [15, 16]. The use of this range of materials in the manufacture of textile products is explained by sufficient hygienic and high strength characteristics. Providing cotton-polyester textile materials with special antibacterial properties will provide increased human protection from the pathogenic effects of the environment.

Intensifier contribute to the swelling of -polyester textile materials before dyeing. In this work, triclosan is used as an intensifier. Due to their small size and affinity for the textile material, intensifiers easily penetrate the fiber, adsorb on active centers and break the bond between neighboring polyester macromolecules. This leads to loosening of the polymer, lowering the glass transition temperature and facilitating the diffusion of the dye into the polyester fiber. And at the same time provides antibacterial properties to the cotton-polyester fabric.

According to the current State Sanitary Norms and Rules "Textile, Leather and Fur Materials and Products. Basic Hygienic Requirements of Ukraine", triclosan is not a prohibited substance. Triclosan is widely used as an antibacterial agent in various fields of application, including hygiene products, textile products and medicine; it is in the manuscript with references to literary sources. The environmental problem of triclosan with other compounds was demonstrated in the articles [7, 10], so they focused more on their original research results. We plan to determine the amount of triclosan in the used dye bath in the process of preparing for industrial use, which requires additional research.

The purpose of this work: to establish the effect of the intensifier concentration on the color intensity, color fastness, on the mechanical properties and antibacterial properties of the fabric of cotton-polyester fabric.

EXPERIMENTS

Materials

For studies as textile materials was used cotton-polyester fabric containing 53% polyester and 47% cotton. This is a fabric with a thickness of 222 ± 5 g/m² and it has a twill weave, see Table 1.

Table 1. Properties of textile substrate.

Yarn fineness (warp)	30–40 tex
Yarn fineness (weft)	30–35 tex
Warp density	~40–45 threads/cm
Weft density	~30–35 threads/cm
Thickness	~0.5–0.8 mm
Surface density	220 g/m ²

Methods

Textile materials with antibacterial properties are prepared as follows. Pretreatment of fabric samples was as follows: dispersing agent (TC-Dispergator DTS, non-ionic, on the basis of polyglycoether-derivates, Textilcolor AG, Switzerland). DTS dispersing agent was poured into a glass, then the intensifier (triclosan CAS: 3380-34-5) was added and mixed thoroughly, adding warm distilled water. The resulting solution was heated to melt the intensifier and whipped until an emulsion was formed. The emulsion for pre-treatment was poured into a vessel with fabric. Treatment of fabric samples with triclosan

emulsion was carried out under the following conditions: bath module 10; DTS dispersing agent concentration – 2 g/l; intensifier concentration (triclosan) 1 – 5 g/l; duration 1 h, temperature 100°C.

Dyeing conditions of polyester fabric component: bath module 10; disperse dye blue 2 BLN CAS: 12217-79-7 (1-3% wt.) (Hongda Chemical Industrial Co., Ltd, China); DTS dispersing agent (2 g/l); acetic acid (CAS: 64-19-7) (1 g/l); duration 1 h; temperature 100°C. Dyeing conditions for the cotton component of the fabric: bath module 10; table salt (40 g/l); active blue dye V-RN (1.5-4% wt.) (Yorkshire Farben GmbH, Germany); soda ash (CAS: 497-19-8) (5 g/l); caustic soda (CAS: 1310-73-2) (2 g/l); duration 85 minutes; temperature 60°C. The dyeing conditions for the cotton component in all experiments were unchanged.

After dyeing, the samples were washed in hot and cold water, and also treated in a soap-soda solution to remove residues of unfixed dye.

The identified color values were classified according to the coordinates set by the Commission International de l'Eclairage - CIELAB 1976 in ISO 2470 standards. To determine the color difference, a Datacolor SF 600 spectrophotometer (Datacolor, USA) was used, which performs measurements according to CIELAB-76. The values of color coordinates and reflection spectra of stained samples are systematized and displayed on a personal computer using the ProPalette program. To conduct the analysis, a reference sample was first measured (with which others were subsequently compared), then the deviation values of such indicators as E, L, C, H of samples stained with an intensifier or stained under other conditions were measured.

The color fastness of the obtained textile material samples to washing (DSTU ISO 105-S06:2009), sweat (DSTU ISO 105-E04:2009), and dry and wet friction (DSTU ISO 105X12:2009) was studied in accordance with standard test methods.

The antimicrobial activity of the samples was determined by the method of zones of inhibition of growth of test strains of microorganisms (DSTU EN 13727:2019). An indicator of the antimicrobial activity of materials is the zone of inhibition of growth of test strains (gram-positive opportunistic microorganisms *Staphylococcus aureus* and gram-negative *Escherichia coli*) around the sample of the tested material.

RESULTS AND DISCUSSION

Textile materials containing polyester fiber systems are characterized by a dense structure. This significantly slows down diffusion processes, therefore, when dyeing such textile materials, high-temperature dyeing methods are used (at a temperature of 130 – 140 ° C under pressure or a thermosol method with a temperature above 200 ° C).

At boiling temperatures, only light color shades can be achieved. To reduce the density of the polymer structure and obtain medium and dark colors at low temperatures, dyeing processes using intensifiers (carriers) have been developed [17-19].

Thus, it is relevant to study the dyeing process of cotton-polyester textile materials with an intensifier - triclosan (5-chloro-2(2,4-dichlorophenoxy)phenol), which has confirmed antibacterial and antimicrobial properties of a wide spectrum of action. The use of this component as an intensifier before the dyeing process of textile materials with a polyester component will allow not only to reduce the temperature, but also to eliminate bactericidal treatment at the stage of final finishing.

Methods of dyeing polyester fabrics using intensifiers make it possible to use less dye and energy resources, diminish the temperature of dyeing and maturation during the obtaining durable and intense colors.

Samples dyed with different concentrations (C, g/l) of intensifier and dye are demonstrated below in Table 2.

As can be seen from the samples, the color intensity increases with increasing concentration of the intensifier. To determine the exact color difference between the samples, we performed an instrumental analysis of the color characteristics. The samples dyed at 130°C were used as reference samples. The samples were analyzed for color differences using a Datacolor SF 600 spectrophotometer (Datacolor, USA). The results are summarized in Table 3.

As can be seen from the data above, with an increase of the intensifier concentration, the general color difference increases, the samples are visibly darker and more saturated, which indicates greater penetration and fixation of the dye inside the fabric.

Furthermore, it can be concluded that achievement of the color intensity obtained under production conditions at 130°C, it is sufficient to use an intensifier in the amount of 1-2 g/l and carry out the dyeing process at 100°C [20].

Comparing the results of the above studies, we can present the results in the form of graphs of dependence of the difference in brightness and general color difference based on the intensifier concentration (C, g/l) (Figures 1, 2).

Under operating conditions, textile materials are exposed to light, moisture, temperature, mechanical forces and various chemical reagents as a result of light exposure, washing, ironing, sweat, dry cleaning, friction, etc.

Under the influence of the above factors, physical-chemical changes occur in the structure of dyes and a violation of the durability of their bond with fibers, which leads to irreversible changes in the color of the material and coloring of the surface it contact with.

Table 2. Samples of cotton-polyester fabrics dyed under different conditions.



















Dyeing conditions	Dispersed blue dye 2 1%, (active blue V-RN 1.5%)	Dispersed blue dye 2 2%, (active blue V-RN 2.5%)	Dispersed blue dye 2 3%, (reactive blue V-RN 4%)
Without intensifier, t=130°C			
With an intensifier 1 g/l, t = 100°C			
With an intensifier 2 g/l, t = 100°C			
With an intensifier 3 g/l, t = 100°C			
With an intensifier 4 g/l, t = 100°C			
With an intensifier 5 g/l, t = 100°C			

Table 3. Analysis of samples by color differences.

C of disperse dye (active)	C of the intensifier	Brightness ΔL	Saturation ΔC	Color saturation ΔH	General color difference ΔE
1% (1,5%)	1 g/l	0,03	-0,19	0,021	0,19
	2 g/l	-0,31	-0,27	0,03	0,41
	3 g/l	-0,39	-0,20	0,022	0,44
	4 g/l	-0,50	-0,29	0,34	0,67
2% (2,5%)	1 g/l	0,05	-0,023	0,16	0,16
	2 g/l	-0,01	-0,19	0,00	0,19
	3 g/l	-0,30	-0,21	0,73	0,82
	4 g/l	-0,90	-0,50	0,07	1,21
3% (4%)	5 g/l	-1,21	-0,63	1,11	1,76
	1 g/l	0,23	0,09	0,54	0,59
	2 g/l	-0,46	-0,33	0,68	0,89
	3 g/l	-0,60	-0,55	0,68	1,06
	4 g/l	-0,67	-1,13	0,13	1,32
	5 g/l	-1,37	-1,26	0,67	1,98

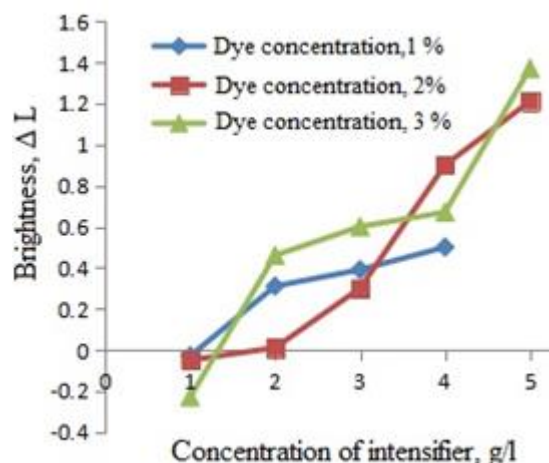


Figure 1. Dependence of the ΔL on the concentration of the intensifier.

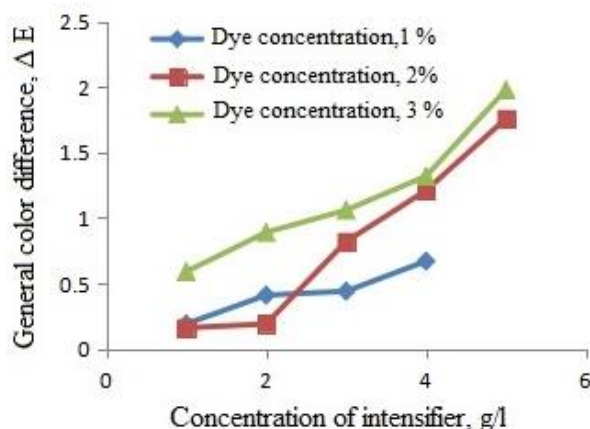


Figure 2. Dependence of the ΔE on the concentration of the intensifier.

Color fastness refers to the ability of textile materials to retain color under the influence of various physical-chemical factors. The resistance of fabrics to various physical-chemical effects is evaluated in points by comparing the test samples with the control samples. The scales of blue and gray reference colors are used as standards. One sample of each scale has the original color and the other samples have colors that differ to some extent from the original, with a score. Moreover, the more stable the color, the higher the score.

Table 4 shows the test results of the colored samples in terms of their color fastness.

All samples dyed at $T=130^{\circ}\text{C}$ without an intensifier and at $T=100^{\circ}\text{C}$ with an intensifier have high resistance to friction and wet treatment.

Based on the data obtained, it can be said that the treatment of fabrics with an intensifier before dyeing does not change the value of indicators of color fastness to physical (friction) and chemical influences (washing and sweat).

It can also be observed that at higher concentrations of the intensifier, the durability of the color increases

slightly. This proves that a larger amount of intensifier allows the dye to penetrate deeper into the fiber.

In the process of manufacturing and exploitation, textile materials are suffered of deformation by stretching, bending, and compression. Indicators of mechanical properties have a great importance into assessing the quality of materials, making a reasonable choice for a product, developing the product design and parameters of the technological process.

To determine the tensile strength characteristics, were used tensile machines we tested untreated polyester and textile material treated with an intensifier (2 g/l) with a DTS dispersing agent (2 g/l) at 100°C for 60 minutes. Tests were also conducted on the fabric to find out how much the intensifier treatment would reduce its strength. For this purpose, several samples of polyester fabric were prepared: dyed at 130°C without the use of an intensifier and samples dyed at 100°C with pretreatment with an intensifier (2 g/l). The results of the yarn and fabric tests are summarized in Table 5.

Based on the data obtained, it follows that the use of an intensifier slightly reduces the strength of the yarn and increases the elongation at break. This is due to the fact that the intensifier breaks the bond between the macromolecules of the polymer and thereby loosens it.

The results of the fabric tests showed that with the use of the intensifier, the breaking load decreased by 2.9% on the warp and 3.3% on the weft, and the elongation increased by 14% on the warp and 12% on the weft. It can be concluded that the use of the intensifier slightly reduces the strength of the thread and to a much lesser extent it affects the fabric.

The phenyl-phenolic intensifier we use not only loosens the structure of polyester fiber, but also has bactericidal properties. To determine the degree of bactericide properties of samples dyed with the intensifier. An indicator of the antimicrobial activity of the materials was the zone of inhibition of growth of test strains (gram-positive opportunistic pathogens *Staphylococcus aureus* and gram-negative *Escherichia coli*) around the sample of the tested material.

Fabric samples were examined:

- with different concentrations of the intensifier (2 g/l and 3 g/l);
- after 5 washings.

The results of the study are summarized in Table 6.

The samples dyeing with the intensifier, high antimicrobial activity is observed for intensifier concentrations of 2 and 3 g/l. From the presented results, it follows that increasing the concentration of the intensifier (above 2 g/l) does not affect the antimicrobial activity.

Table 4. Indicators of color fastness.

C of Inten- sifier (dyeing t°C)	C of dye	Color fastness, points			
		sweat	soap	wet fric- tion	dry fric- tion
without	1%	5/5	5/5	4	4
intensifier	2%	5/4-5	5/5	4	4
(130°C)	3%	5/4-5	5/5	4-3	3-4
1 g/l	1%	5/5	5/5	4	4
(100°C)	2%	5/4	5/4-5	4	4
	3%	4/4	5/4	4	3
2 g/l	1%	5/5	5/5	4	4
(100°C)	2%	5/4	5/4-5	4	4
	3%	5/4	5/4	4	4
3 g/l	1%	5/5	5/5	4-5	4
(100°C)	2%	5/4	5/5	4	4
	3%	4/4	5/5	4	3-4
4 g/l	1%	5/5	5/5	4-5	4
(100°C)	2%	5/5	5/5	4-5	4
	3%	5/5	5/5	4	4
5 g/l	1%	5/5	5/5	4-5	4
(100°C)	2%	5/5	5/5	4	4
	3%	5/5	5/5	4	4

Table 5. Indicators of tensile strength.

Sample	Breaking load P _b [N]	Elongation at the moment of break [%]
Polyester		
Control sample	19,27± 0,3	7,13±1
After treatment with intensifier	18,25± 0,3	13,06±1
Dyed fabric (base)		
without intensifier	615±5	22,9±1
with pre-treatment by an intensifier	597±5	26,2±1
Dyed fabric (weave)		
without intensifier	575±5	30,4±1
with pre-treatment by an intensifier	556±5	34,1±1

Table 6. Evaluation of antimicrobial activity.

Sample	The value of the indicator	Actual value
1 sample (C = 2 g/l)	not less than 4 mm	*S. aureus 49 mm *E. coli 36 mm
2 sample (C = 3 g/l)	not less than 4 mm	*S. aureus 46 mm *E. coli 34 mm
3 sample (C = 2 g/l) after 5 washings	not less than 4 mm	*S. aureus 34 mm *E. coli 0 mm

*S. aureus ATCC 6538 test strains for Staphylococcus aureus;

*E. coli ATCC 8739 test strains for Escherichia coli.

CONCLUSION

The proposed method confirms the feasibility of using the selected intensifier when dyeing cotton-polyester textile materials. The concentrations of the intensifier during their finishing were determined. Dyeing cotton-polyester textile material using triclosan as an intensifier allows to reduce the dyeing temperature to 100°C. The use of triclosan concentrations when

finishing textile materials before dyeing from 1 g/l to 5 g/l increases the intensity of the dyeing, which especially affects the obtaining of deep and saturated color characteristics. At intensifier concentrations of 4 g/l and 5 g/l, the resistance of the dyeing to physicochemical influences increases, therefore, the intensifier allows the dye to penetrate deeper into the fiber structure. The introduction of triclosan in an amount of 2 g/l is sufficient to obtain high-quality antibacterial characteristics of dyed textile materials.

Thus, the effect of the intensifier on the intensity of the color and its resistance to physicochemical factors was established. The effective use of the intensifier with antibacterial action in the dyeing of cotton-polyester textile materials was confirmed.

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PRODUCTION OF NANOFIBERS USING ELECTROSPINNING WITH THE USE OF METAL LAMS

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ABSTRACT

This study presents a novel design for an industrial electrospinning system aimed at the large-scale production of nanofibrous materials. The proposed system utilizes electrospinning of a polymer solution or melt within a high-intensity electric field generated between the collection electrodes and the polymer solution or melt deposited on the spinning apparatus. The developed machine is designed to achieve performance comparable to or exceeding that of existing electrospinning devices. In its basic configuration, the system operates with a single spinning head and a single collecting electrode. However, the design allows for scalability, accommodating up to six spinning heads and six corresponding collecting electrodes, thereby significantly enhancing production efficiency. Furthermore, the modular design enables flexible operation, allowing for the selective use of spinning heads to adapt to varying production demands. This adaptability, along with the capacity for customization, distinguishes the proposed system from existing technologies, making it suitable for both industrial applications and research-oriented modifications.

KEYWORDS

Nanofibers; Needle-less; Electrospinning; Production.

INTRODUCTION

Nanofibers have gained significant attention due to their unique properties, including a high surface-area-to-volume ratio, tunable porosity, and exceptional versatility in biomedical, filtration, and textile applications. These ultrafine fibers provide an excellent platform for drug delivery, wound healing, air and liquid filtration, and protective textiles due to their ability to mimic the extracellular matrix, provide high permeability, and support controlled release of active agents [1,2]. The growing interest in nanofibers has led to the development of various fabrication methods, each relying on distinct physical and chemical principles, including phase separation, template synthesis, self-assembly, and electrospinning [3]. Among these, electrospinning has emerged as the most effective and scalable technique, allowing for the continuous production of nanofibers with controlled morphology and tailored properties. This method utilizes a high-voltage electric field to transform a polymer solution or melt into ultrafine fibers, which solidify upon solvent evaporation or cooling [4,5].

Electrospinning has a long and well-documented history, with the first patent dating back to 1902 by

J.F. Cooley [6], followed by subsequent refinements by Formhals in the 1930s. Despite its early discovery, electrospinning gained widespread recognition only in the late 20th century due to advances in nanotechnology and materials science [7]. The fundamental process of electrospinning involves the application of an external electric field to a polymer solution or melt, generating a charged polymer jet at the Taylor cone. As the solvent evaporates, the polymer solidifies into continuous nanofibers, which are deposited onto a collector. The properties of the resulting nanofibers are influenced by multiple interdependent parameters, including polymer solution characteristics (e.g., viscosity, concentration, surface tension, dielectric properties), processing factors (e.g., applied voltage, flow rate, electrode geometry, collection distance), and environmental conditions (e.g., humidity, temperature, airflow) [8–13]. Almetwally et al. [19] provided a comprehensive review of nanofiber production parameters and their impact on fiber morphology. Their study emphasized the importance of precise control over polymer solution properties and processing conditions to achieve uniform nanofiber structures. Understanding and optimizing these parameters is critical for producing nanofibers with consistent diameters,

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mechanical integrity, and application-specific properties.

Among the various electrospinning configurations, needle-based electrospinning remains widely used in laboratory research due to its ability to produce well-defined fibers. However, its limited production rate and susceptibility to clogging restrict its industrial scalability [14]. To address these limitations, needle-less electrospinning has emerged as a highly efficient alternative for large-scale fiber production. In this technique, a high-voltage electric field acts on a polymer solution or melt distributed over a rotating spinning electrode, such as a cylinder, disk, or wire array [15,16]. Unlike traditional needle-based electrospinning, needle-less techniques enable the simultaneous formation of multiple Taylor cones along the electrode's surface, significantly increasing productivity.

One of the key challenges associated with needle-less electrospinning, however, is the inability of the spinning electrode to effectively mix the polymer solution within the reservoir. Unlike needle-based setups where fresh polymer solution is continuously supplied via a syringe pump, needle-less electrospinning relies on a bulk reservoir that is exposed to prolonged processing times. Due to the low rotational speed of the spinning electrode (typically a few revolutions per minute) and its limited dimensions, the polymer solution undergoes gradual thickening, solvent evaporation, and potential chemical degradation. As a result, the viscosity of the solution increases over time, leading to fiber diameter inconsistencies, reduced spinning efficiency, and eventual process failure. This issue is particularly problematic for high-molecular-weight polymers and volatile solvents, which exacerbate solution instability.

To overcome this limitation, various mixing strategies have been proposed. For instance, Wei et al. [17] developed a needle-less electrospinning system incorporating a cylindrical collecting electrode, achieving a maximum nanofiber productivity of 4.5 g/hour. Their study demonstrated that fiber diameter increased proportionally with polymer concentration, and the produced nanofibers exhibited promising filtration performance. However, the lack of active solution mixing resulted in polymer thickening over time, affecting long-term stability. Similarly, Kim et al. [18] designed an air-jet electrospinning spinneret to enhance fiber uniformity in thermoplastic and thermoset polymer nanofibers. While effective for specific polymer systems, this approach did not address the fundamental issue of solution homogeneity in needle-less electrospinning. Furthermore, Bryner et al. [20] patented an improved electrospinning process in which voltage was directly applied to a pair of electrodes placed parallel to a grounded spinneret, overcoming disadvantages associated with conventional voltage application

methods. These studies collectively highlight the need for optimized electrospinning systems that balance productivity, fiber quality, and process stability.

Despite these advancements, a significant gap remains in addressing polymer solution thickening and degradation during extended needle-less electrospinning processes. Conventional mixing solutions, such as the integration of mechanical stirrers or ultrasonic agitation, introduce additional complexity, increase energy consumption, and require larger reservoirs to prevent interference with the spinning electrode. For example, the introduction of a moving auger within the polymer reservoir, as proposed in [21], successfully enhanced solution homogeneity but required additional mechanical components, increasing system complexity and costs.

This study aims to address the challenges associated with solution homogeneity in needle-less electrospinning by developing a novel mixing strategy that ensures consistent polymer solution properties without compromising process efficiency. The proposed approach is evaluated in terms of its impact on fiber morphology, productivity, and overall electrospinning performance. By optimizing solution stability, the operational lifespan of needle-less electrospinning setups can be extended, enabling the production of uniform, high-quality nanofibers suitable for industrial applications. Addressing one of the key limitations of current needle-less electrospinning systems, this research contributes to the advancement of scalable electrospinning technologies, supporting their broader adoption in biomedical engineering, filtration systems, and functional textiles. The findings offer valuable insights into improving nanofiber manufacturing processes, facilitating the transition from laboratory-scale research to large-scale commercial production.

EXPERIMENTAL PART

Design and construction of novel electrospinning device

Based on the principles of various spinning technologies previously outlined, a specialized electrospinning agent has been designed to ensure full coverage of the substrate's width, which is typically 1600 mm in industrial-scale operations. The spinning agent is designed to operate within a container filled with a polymer solution or melt. One of the most advantageous features of this design is the use of a bar, as illustrated in Fig. 1(b), which shows the shape of the bar used in the proposed device. The upper edge of the bar is utilized to create a Taylor cone (Fig. 2). Additionally, the bar's horizontal, rectilinear motion helps mix the polymer solution or melt, preventing degradation and ensuring extended usability of the polymer solution for

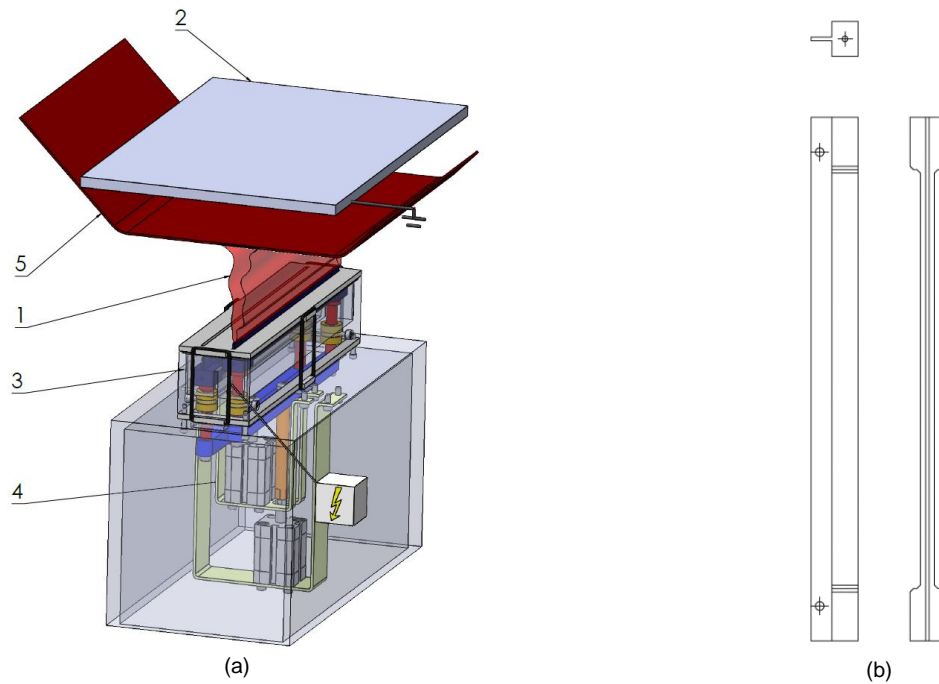


Figure 1. Machine concept. (a) (1) emerging nanofibers, (b) grounded collector, capturing nanofibers, (3) polymer solution or melt in a container, (4) bars with drives, (5) substrate for nanofibers. (b) Bar shape used in the proposed device.

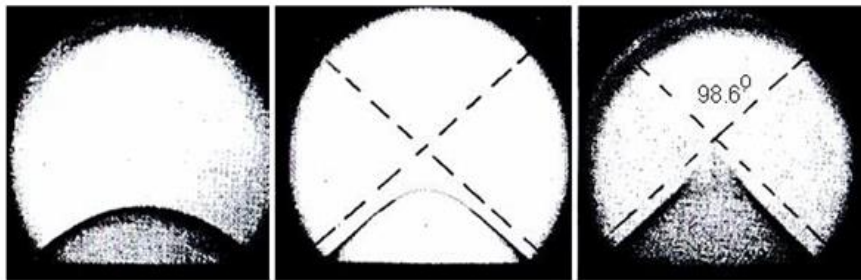


Figure 2. Taylor cone [7].

electrospinning. This dynamic motion contributes to the long-term stability of the polymer and ensures high-quality nanofiber production. The prototype of the device designed for electrospinning a polymer solution or melt is depicted in Fig. 1(a), where two spinning heads work in a rectilinear reciprocating motion within a container filled with the polymer solution. The design and operation of this system are optimized to facilitate efficient electrospinning for industrial-scale production.

Fig. 3 (a) provides a schematic cross-section of the electrospinning device equipped with a single spinner, while Fig. 3 (b) showcases the cross-section of a dual-spinning nanofiber production system utilizing the proposed device. The spinner is constructed from an electrically non-conductive material, in this case, stainless steel, with its upper edge positioned towards the collecting electrode, which is located above the spinner. The spinner can be adjusted in the solution reservoir between two distinct positions: the working position (represented by the dotted position P), where the edge of the spinner is closest to the collecting electrode, and the resting position (dotted position K), where the spinner is furthest from the electrode. The polymer solution is

applied to the spinner in such a way that, in its resting position, the spinner is submerged below the surface of the polymer solution, ensuring an even coating of the polymer solution for optimal electrospinning. The spinner operates in a straightforward motion, with a pneumatic cylinder driving the movement of each spinner located below the magazine. The pneumatic cylinder activates the lifting mechanism, which must be perfectly sealed with a rubber gasket to prevent leakage as it moves through the polymer solution reservoir. The spinners are equipped with side holes, facilitating easy handling, removal, and storage.

Tests demonstrated that the straight edge of the spinner was the most effective design, as it simplifies cleaning and ensures even distribution of the polymer solution. To maintain a consistent level of the polymer solution or melt, the solution reservoir is equipped with an inlet and outlet system (not shown), including an overflow mechanism. This system helps ensure the polymer solution remains at the optimal level throughout the electrospinning process.

During the electrospinning process, a high voltage of negative polarity is applied to the collecting electrode, while the polymer solution or melt is subjected to a high voltage of opposite polarity.

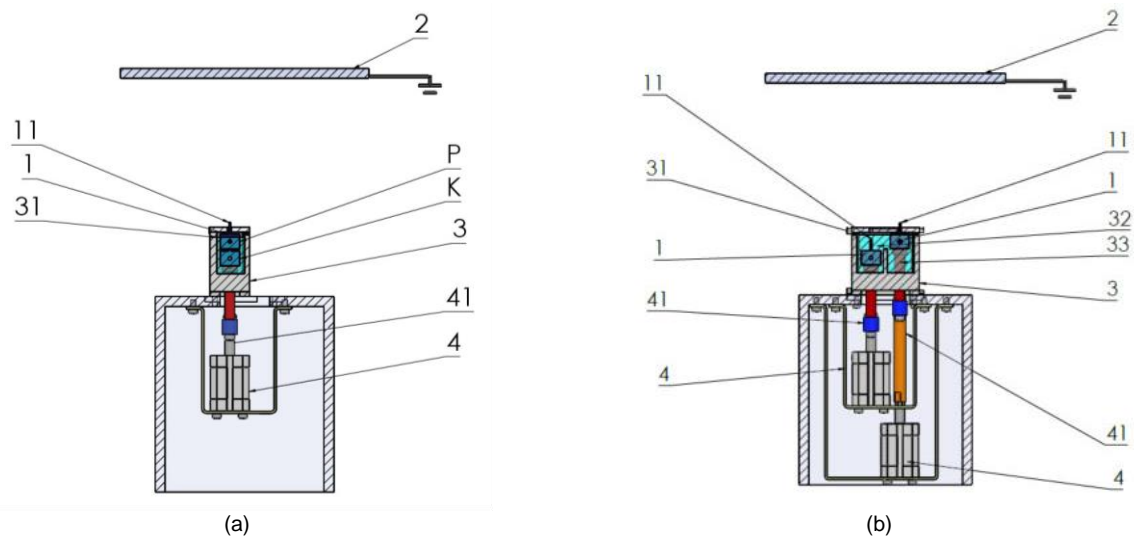


Figure 3. Cross-section of the proposed device(s) with a (a) single spinner; and (b) with two spinners. (1) Spinners, (2) collection electrode, (3) polymer reservoir, (4) double-acting pneumatic motor, (11) edge of the spinneret, (31) polymer or melt level, (32) baffle, (33) polymer solution or melt, (41) movement mechanism, (P) working position, (K) rest position.

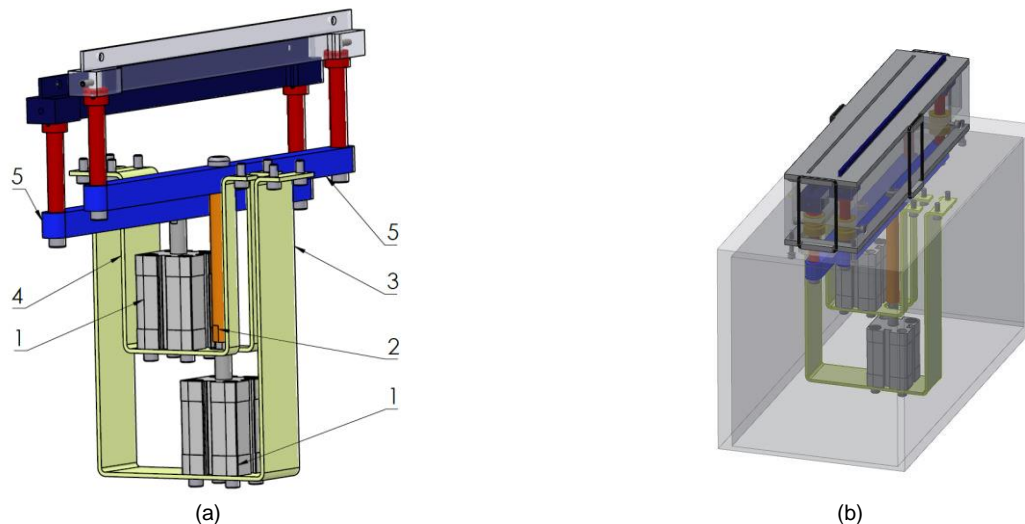


Figure 4. (a) Motion gear with rails and tie rods fitted. (1) Pneumatic drive, (2) piston rod extension, (3) pneumatic drive mount, (4) pneumatic drive mount, (5) tie rod connecting piece. (b) View of the prototype of the machine itself.

As the polymer solution is drawn toward the spinner, the spinner moves to its working position under the influence of its drive system, bringing it closer to the collecting electrode. At this point, electrostatic forces induce the formation of Taylor cones at the tips of the polymer solution. The polymer solution is then elongated, forming nanofibers that are continuously deposited onto the surface of a flat substrate. Once a predetermined amount of polymer solution has been applied, and after a pre-set time interval, the spinner returns to its resting position, moving away from the collecting electrode. The cyclic movement of the spinner through the polymer solution not only ensures the uniform deposition of nanofibers but also facilitates the mixing of the polymer solution, enhancing the lifespan of the solution and minimizing the risk of chemical degradation.

After the spinner completes a cycle of deposition, the polymer solution or melt is refreshed, and the electrospinning process continues. This cyclical

movement of the spinner, combined with the mixing of the polymer solution, results in enhanced solution stability and optimal nanofiber quality.

A functional prototype of the electrospinning device was assembled to verify the operational effectiveness of the design, as shown in Fig. 4(a). This prototype serves as the basis for trial production, and it is anticipated that the system will be integrated into the existing Nanospider. The completed machine, shown in Fig. 4(b), incorporates the key features necessary for large-scale electrospinning.

The final machine design will feature six spinning heads, allowing for simultaneous production from multiple spinners, enhancing the efficiency and scalability of the nanofiber manufacturing process. Fig. 5 presents an overall view of the intended design of the machine, highlighting the main components essential for the operation and control of the device. This design incorporates knowledge gained from the testing and evaluation of the prototype described

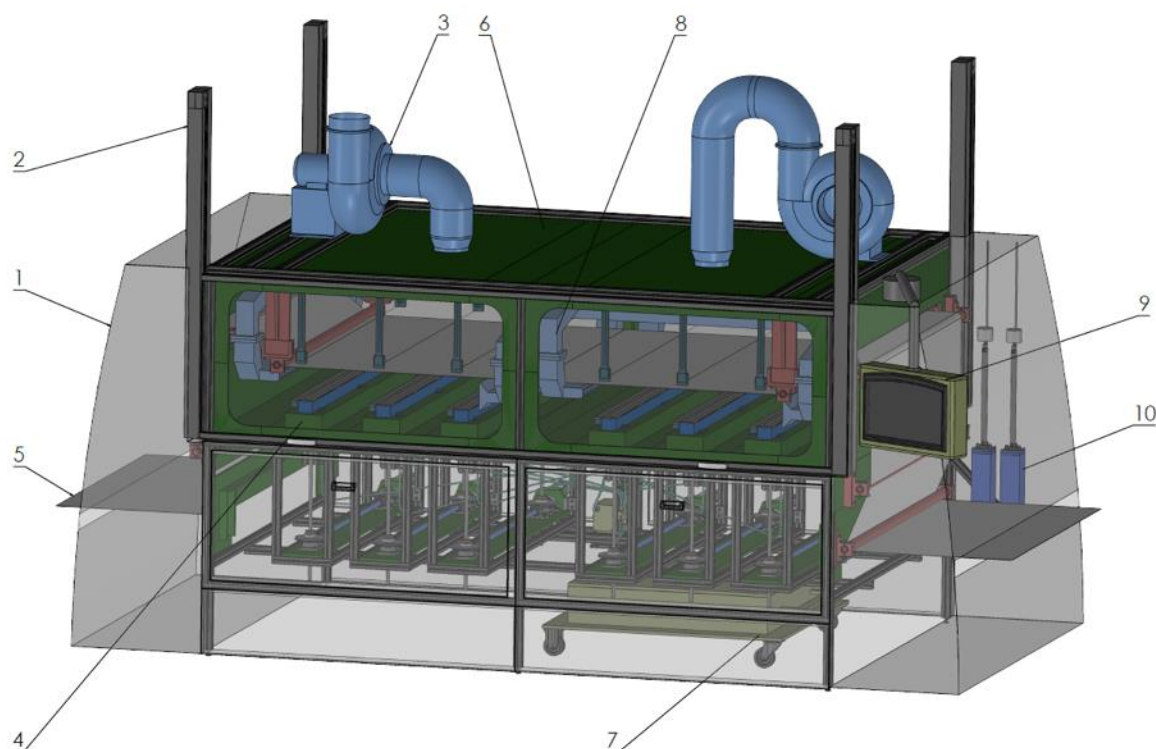


Figure 5. Machine concept. (1) Machine cover, (2) Machine frame, (3) Acid-proof fan, (4) Spinning head, (5) Base, (6) Spinning proctor, (7) Polymer distribution, (8) Ventilation, (9) Control panel, (10) dischargers.

earlier, excluding the electrical components, which will be addressed in subsequent studies. A more detailed description of the individual parts and components of the machine can be found in previous work on the subject [20].

The proposed device offers several advantages over conventional electrospinning methods, particularly in terms of solution handling and fiber deposition consistency. Traditional electrospinning systems often face challenges in maintaining uniform solution delivery and preventing polymer solution degradation. In contrast, the innovative spinner design in this system effectively addresses these issues by continuously mixing the polymer solution while ensuring stable electrospinning conditions. The dynamic, back-and-forth motion of the spinner facilitates even solution distribution across the spinning surface, minimizing the risk of solution pooling or degradation. This approach enhances fiber uniformity and improves overall process efficiency, making it a promising advancement for large-scale nanofiber production.

Performance of the developed electrospinning device

To perform the electrospinning process, the polymer solution for producing polyamide nanofibrous layers was prepared by dissolving polyamide 9T. in a mixture of acetic and formic acid (56/34 v/v), yielding a 10% polymer solution. The solution was mixed for approximately 3 minutes using a magnetic stirrer to

ensure a homogeneous distribution. Polyamide 9T was selected due to its long aliphatic chain consisting of nine methylene groups, which provide excellent thermal stability and low water absorption. This polymer was chosen to produce the nanofibrous layer, as it offers ease of fabrication and desirable properties for various applications. A spunbond nonwoven fabric with an area weight of 29 g/m² was used as the substrate. The prepared polymer solution was then added to the reservoir containing the spinning bars, and the solution was subjected to an electric field with a voltage of 69.5 kV. A condenser was positioned above the solution tray at a distance of 190 mm. The supporting base fabric was moved at a speed of 0.1 m/min to ensure uniform deposition of nanofibers. The areal weight of the resulting nanofibrous layers was 1 and 2 g/m². The morphology of the fabricated nanofibrous layers was evaluated using scanning electron microscopy (SEM), as shown in Fig. 6.

Image analysis revealed that the electrospun nanofibers exhibited an average fiber diameter of 715 ± 190 nm. Pore structure analysis indicated that the maximum Feret diameter of the pores reached 0.67 ± 0.3 μ m, while the equivalent diameter of the pores was measured at 0.52 ± 0.25 μ m. These values suggest a relatively uniform fiber morphology with a well-defined porous network, which is crucial for applications requiring controlled permeability, such as filtration, tissue engineering, and drug delivery. The observed variation in fiber diameter and pore size distribution can be attributed to factors such as

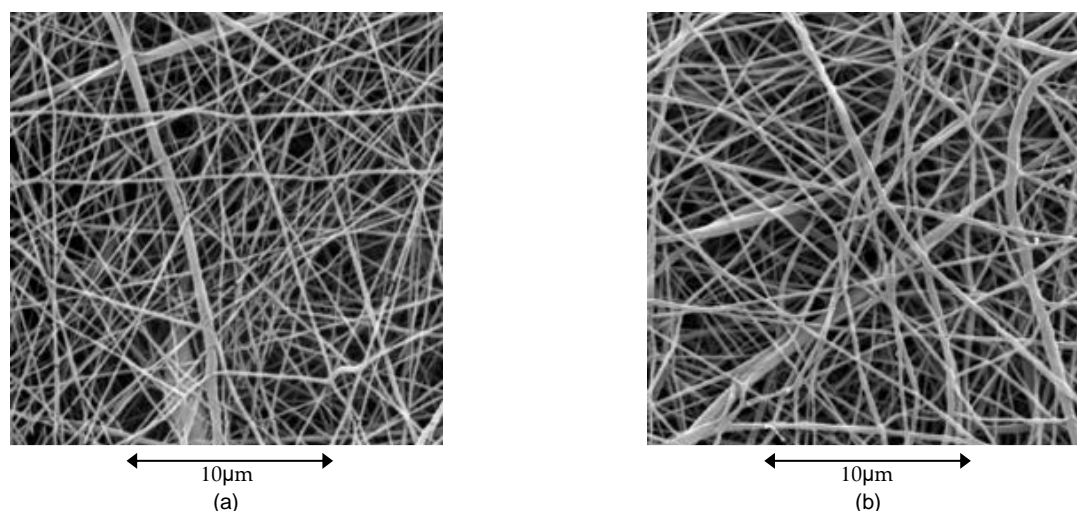


Figure 6. SEM of a nanofibrous membrane with areal weights: (a) 1 g.m⁻², (b) 2 g.m⁻².

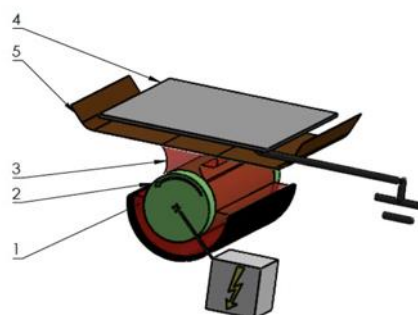


Figure 7. (1) Polymer solution or melt, (2) roller, high voltage source, (3) emerging nanofibers, (4) grounded collector, capturing nanofibers, (5) substrate for nanofibers.

polymer solution viscosity, electrospinning parameters, and environmental conditions during fabrication. Further optimization of processing conditions may help reduce variability and achieve even greater control over nanofiber dimensions and porosity.

To benchmark the proposed electrospinning system, its performance was compared to that of the Nanospider™ system, an industrial-scale nanofiber production technology. Developed by Prof. Jirsák at the Technical University in Liberec and manufactured by Elmarco (Czech Republic), Nanospider™ employs nozzle-free electrospinning. Instead of capillary nozzles, it utilizes a rotating cylinder or string partially immersed in a polymer solution (Fig. 7). As the cylinder rotates, a thin polymer film forms on its surface, where a high-voltage electric field induces Taylor cone formation, initiating electrospinning. This approach enables high-throughput production and makes Nanospider™ one of the most efficient needleless electrospinning technologies.

Fig. 8 presents SEM images of nanofibrous layers produced by both systems at magnifications of 50× and 3000×, providing a visual comparison of fiber morphology and distribution. These results demonstrate that both technologies produce

nanofibers with uniform diameters and pore structures.

A detailed image analysis was performed to compare the fiber morphology, pore structure, and uniformity of nanofibrous layers obtained from the Nanospider™ and the proposed device (Table 1). The results showed that the proposed system produced nanofibers with an average diameter of 715 ± 190 nm, which is slightly larger than the 625 ± 200 nm observed for the Nanospider™. The equivalent pore diameter was 0.52 ± 0.25 μm for the proposed device and 0.56 ± 0.30 μm for the Nanospider™. The maximum Feret diameter of the pores measured 0.67 ± 0.30 μm for the proposed device, compared to 0.87 ± 0.58 μm for the Nanospider™. The pore density per cm² was comparable between the two systems, with the proposed device producing 87.2×10^6 pores/cm² and the Nanospider™ yielding 89.5×10^6 pores/cm².

DISCUSSION

Several industrial companies have developed scalable electrospinning technologies to overcome the limitations of traditional laboratory-scale methods. These advancements aim to enhance production efficiency, fiber uniformity, and adaptability to various material systems. One such company, SPUR a.s., has implemented multiple nanofiber production

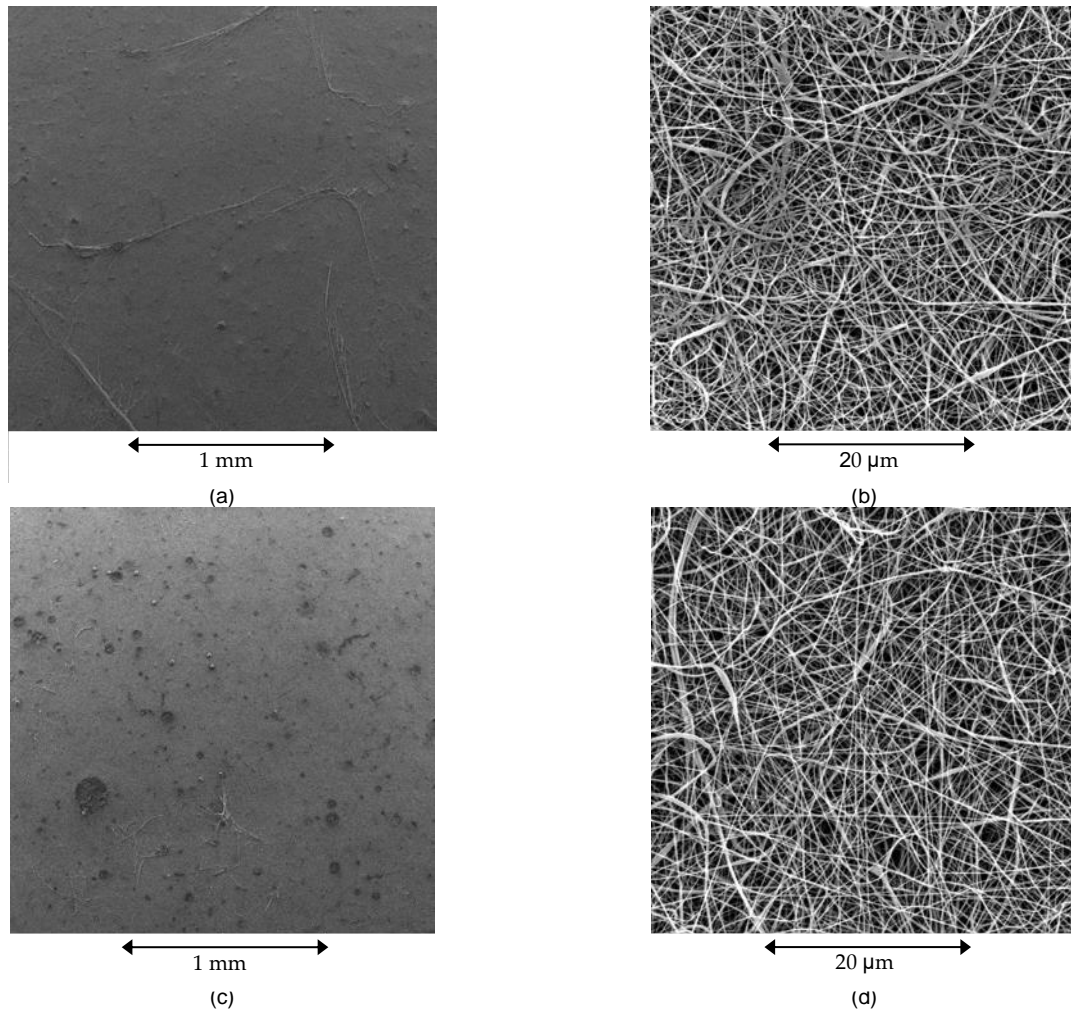


Figure 8. Nanofibrous layer made on Nanospider, (a) SEM, 50x, (b) SEM 3000x, Nanofibrous layer made on a proposed device (c) SEM, 50x, (d) SEM, 3000x.

Table 1. Evaluation of nanofibrous layers produced on Nanospider and proposed device.

		Number of pores [cm ⁻²]	Max Feret of pores [μm]	Eq. diam. of pores [μm]	Fiber diameter [nm]
Nanospider	Mean	89563758	0.87	0.56	625
	SD	2526152	0.58	0.30	0.20
Proposed device	Mean	87235952	0.67	0.52	715
	SD	2052649	0.30	0.25	0.19

techniques, including electrostatic spinning, melt spinning, and electric blowing (Fig. 9). Each method offers distinct advantages depending on the target application, polymer compatibility, and scalability requirements. Electrostatic spinning, similar to our approach, utilizes an electric field to generate nanofibers. Industrial-scale adaptations include multi-nozzle electrospinning for higher throughput and needleless/free-surface electrospinning, as seen in Nanospider™ technology. These modifications enhance scalability while maintaining fiber morphology and uniformity. Melt spinning, unlike solvent-based electrospinning, this technique relies on polymer melt extrusion, eliminating the need for volatile organic solvents. This improves environmental and safety profiles, making it a viable option for large-scale nanofiber production. However, it is restricted to thermoplastic polymers with

appropriate melt viscosities, limiting material selection. Electric blowing, a hybrid method combining electrospinning with air-jet technology, increasing deposition rates. This approach improves throughput but requires careful optimization to prevent fiber defects, ensuring consistency in diameter distribution and surface properties. Compared to the scalable technologies employed by SPUR a.s., our proposed electrospinning system offers greater flexibility for solution-based fiber production, particularly in applications requiring precise fiber morphology, surface functionalization, and post-processing modifications. However, further optimization is necessary to achieve production rates comparable to SPUR a.s.'s industrial methods.

Beyond conventional electrospinning, several alternative nanofiber production techniques have been explored to improve scalability, efficiency, and

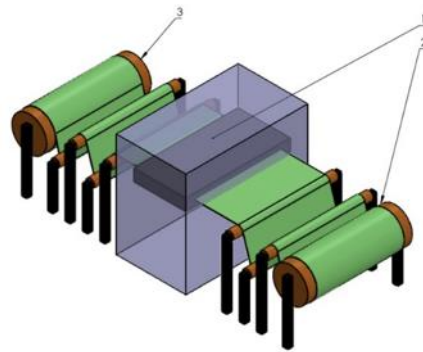


Figure 9. SPUR-line Spinning process: (1) spinning space, (2) winding, (3) unwinding.

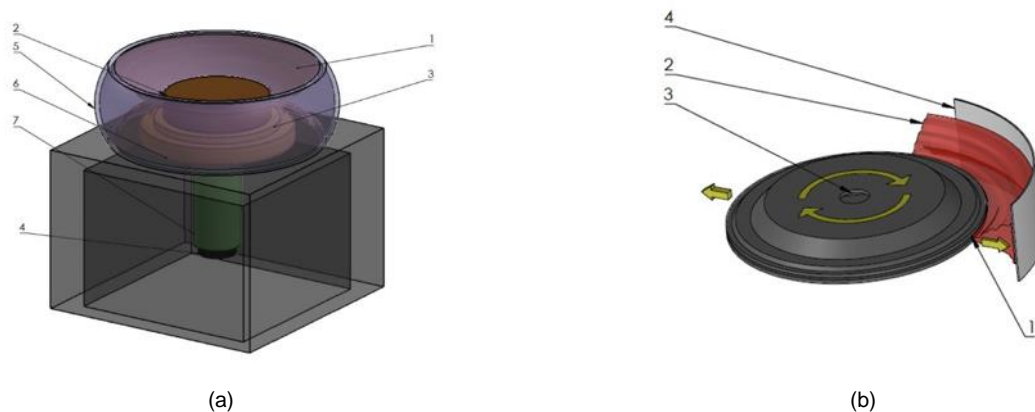


Figure 10. Force-spinning process. (a) (1) forming nanofiber, (2) spinneret, (3) furnace, (4) brake, (5) nanofiber catcher, (6) heater, (7) motor. (b) (1) opening, (2) forming nanofiber, (3) material supply, (4) nanofiber catcher.

material versatility. Two notable approaches are air-jet electrospinning and forcespinning, both of which offer advantages over traditional electrostatic methods. Air-Jet electrospinning integrates a high-velocity air stream into the electrospinning process, assisting in fiber elongation and deposition. By reducing reliance on strong electric fields, air-jet electrospinning enhances throughput and deposition uniformity while maintaining nanoscale fiber diameters. The process is particularly advantageous for high-speed production lines, making it a promising alternative for large-scale nanofiber manufacturing. Forcespinning (FibeRio Technology Corporation), unlike electrospinning, relies on electrostatic forces, forcespinning utilizes centrifugal force to draw fibers from a rotating drum (Fig. 10). This technique significantly increases productivity by eliminating the limitations imposed by electrostatic charge accumulation. The system can process both polymer solutions and melts, broadening the range of compatible materials. The core mechanism involves a high-speed rotating nozzle, which, when heated, melts the polymer and extrudes fibers under centrifugal force. The stretching force further refines fiber diameter and morphology, with the nanofibers subsequently collected by a capture electrode. While forcespinning enables high-throughput nanofiber production, challenges remain in controlling fiber diameter and uniformity, particularly for applications requiring precise nanoscale dimensions.

Comparison and future considerations

Nanofiber production techniques, as discussed, vary significantly in their scalability, fiber control, and application suitability. While methods such as melt spinning and force-spinning prioritize high production rates and solvent-free processes, electrostatic and air-jet electrospinning offer better control over fiber morphology and functionalization. Each method has distinct advantages, with melt spinning and force-spinning excelling in scalability but lacking fine control over fiber structure. In contrast, electrostatic and air-jet electrospinning allow for more precise tailoring of nanofiber properties, making them ideal for specialized applications like biomedical and filtration.

The proposed electrospinning system stands out as a solution to bridge the gap between high scalability and precise fiber control. It offers a customizable platform that can be adapted for various polymer solutions and application needs, making it versatile for different industries, particularly medical, textile, and filtration fields. However, competing with industrial-scale systems like those developed by SPUR a.s. and FibeRio Technology Corporation requires ongoing improvements in production speed, fiber consistency, and material adaptability.

The proposed electrospinning system offers several innovations that address key challenges in nanofiber production. One of the standout features is the novel electrospinning device designed for large-scale

production, which combines the benefits of dynamic mixing and a receding spinner motion. This unique design ensures consistent solution mixing, prevents polymer degradation, and improves fiber uniformity during the electrospinning process. Additionally, the rectangular spinner design with horizontal, rectilinear motion enhances the uniform coating of the polymer solution, reducing variability in fiber morphology. The inclusion of six spinning heads allows for simultaneous production of nanofibers, significantly increasing throughput compared to traditional single-spinner systems. This design is ideal for industrial applications, particularly in sectors like medical and filtration, where high-volume production is necessary without compromising fiber quality. Furthermore, the system's ability to cover a large substrate width of 1600 mm addresses the long-standing challenge of scaling up electrospinning from laboratory-scale to industrial-scale operations, making it a competitive solution for commercial use.

Despite its promising capabilities, the proposed electrospinning system faces challenges, particularly in terms of setup and maintenance costs. The integration of multiple spinners, mixing systems, and precision control mechanisms demands significant investment in equipment and operational expertise. The reliability of the spinner's motion and solution delivery over extended production cycles also needs thorough testing to ensure consistent performance in industrial settings. Furthermore, while the current system demonstrates good fiber consistency, there remains room for improvement in controlling nanofiber morphology on a finer scale, particularly concerning fiber diameter and distribution. Future research should focus on optimizing processing parameters, refining fiber alignment strategies, and exploring hybrid approaches that combine the benefits of multiple techniques. By integrating advances from multi-nozzle electrospinning, air-assisted deposition, and centrifugal processing, future systems could enhance both scalability and precision.

Additionally, optimizing the deposition rate while maintaining fiber quality will be critical for future advancements in nanofiber manufacturing. Incorporating different polymer solutions, such as biodegradable polymers or bioactive compounds, could open new possibilities for specialized applications in wound healing, drug delivery, and tissue engineering. The flexibility of the proposed system also allows for the production of multi-layered scaffolds with customized properties, such as varying porosity, hydrophilicity, and mechanical strength, offering exciting opportunities for multifunctional material design.

CONCLUSION

In conclusion, the proposed electrospinning device demonstrates significant potential for industrial-scale nanofiber production. The novel design, with its

dynamic spinner motion and multiple spinning heads, offers improved consistency, scalability, and operational efficiency compared to traditional electrospinning systems. The system's ability to mix the polymer solution in real-time and deliver uniform nanofibers positions it as a promising solution for high-throughput, large-area nanofiber fabrication.

While the device is in the prototype phase, preliminary results suggest it could have a substantial impact on the future of nanofiber manufacturing, particularly in sectors requiring high-quality, scalable materials. Continued development and optimization of the system, including cost analysis, long-term testing, and further exploration of customization options, will be essential to fully realize its industrial potential.

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AIMS AND SCOPES

“Vlákna a Textil” is a peer-reviewed scientific journal serving the fields of fibers, textile structures and fiber-based products including research, production, processing, and applications.

The birth of this journal is connected with three institutions, Research Institute for Man-Made Fibers, Svit (VÚCHV), Research Institute of Chemistry of Textiles (VÚTCH) in Žilina and Department of Fibers and Textiles at the Faculty of Chemical Technology, Slovak Technical University in Bratislava, having a joint intention to provide, utilize and deposit results obtained through the research, development and production activities dealing with the aforementioned scopes. „Vlákna a Textil“ journal has been launched as a consequence of a joining of existing magazines „Chemické vlákna“ (VÚCHV) and „Textil a chémia“ (VÚTCH). Their tradition should provide a good framework for the new journal with the main aim to create a closer link between the basic element of the product - fibre and its fabric - textile.

Since its founding in 1994, the journal introduces new concepts, innovative technologies and better understanding of textile materials (physics and chemistry of fiber forming polymers), processes (technological, chemical and finishing), garment technology and its evaluation (analysis, testing and quality control) including non-traditional applications, such as technical textiles, composites, smart textiles or garment, and nano applications among others. The journal publishes original research papers and reviews. Original papers should present a significant advance in the understanding or application of materials and/or textile structures made of them.

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