

A Study on Antibacterial Finish on Bamboo Fabric using Plant Extract

S. M. Naseera^{1*}, R. Prabha¹ & V. Ramya³

^{1*2}Department of Textiles and Clothing, School of Home Science, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore, TN, India

Abstract:

Purpose: In response to the rising global interest in natural remedies and the need for sustainable textile practices, this study investigates the potential of medicinal plant extracts as eco-friendly antibacterial finishes for bamboo fabric. The purpose is to explore the utilization of plant extracts not only as natural dyes but also as effective antibacterial agents, aiming to enhance the eco-friendliness and antimicrobial properties of bamboo textiles.

Design/Methodology/Approach: The study employs a comprehensive approach by first assessing the phytochemical composition of *Basella alba*, *Jacaranda mimosifolia* D. Don, and *Moringa oleifera* Lam. Extracts from these medicinal plants are obtained using acetate, methanol, and petroleum ether solvents. Antibacterial activity is evaluated using the EN ISO 20645 test method against *Escherichia coli* and *Staphylococcus aureus*. Fabric finishing is conducted by treating bamboo fabric with a solution comprising 1% medicinal plant extracts, 1% acrylic binder, and 0.5% wetting agent, followed by standard finishing techniques.

Findings: The plant extracts contain bioactive substances such as alkaloids, flavonoids, terpenoids, phenols, and tannins, according to the phytochemical analysis. When it comes to test microorganisms, methanol extracts have the strongest antibacterial activity. Their inhibitory zones span roughly 16 to 20 mm. Treated bamboo fabric samples demonstrate significant antibacterial efficacy, with inhibitory zones measuring approximately 24 to 28 mm against *Escherichia coli* and *Staphylococcus aureus*.

Originality: This study contributes to the area by showing the potential of medicinal plant extracts as both natural dyes and efficient antibacterial treatments for bamboo fabric. The eco-friendly approach to fabric finishing is consistent with the rising need for sustainable textile techniques. Furthermore, including plant extracts into fabric treatments provides a unique method for improving antibacterial capabilities while maintaining environmental sustainability.

Conclusion: The findings highlight the efficacy of medicinal plant extracts to enhance the antibacterial properties to bamboo fabric and bringing up possibilities for the development of environmentally friendly and antimicrobial textiles for wide range of applications.

Keywords: Antibacterial agent, Bamboo fabric, *Basella alba*, *Jacaranda mimosifolia*, *Moringa oleifera* Lam.,

*Corresponding Author:

Mr. S. M. Naseera

Department of Textiles and Clothing,

School of Home Science,

Avinashilingam Institute for Home Science and Higher Education for Women,

Bharathi Park Road, Saibaba Colony,

Coimbatore – 641 043 TN

1. Introduction

Natural dyes are widely available in India and its subcontinent, with a significant potential for generating a wide spectrum of skin tones while being eco-friendly [1]. A growing understanding of the non-toxic and non-allergic qualities of natural colors, as well as the allergic and toxic effects of some synthetic dyes [2]. In recent times, consumer and textile manufacturers have expressed an interest in natural dyes, citing their manufacturer product need to claim biodegradability, eco-compatibility, therapeutic efficacy, as well as the antibacterial and UV protecting properties [3]. Textiles have long been recognized as a growing substrate for microorganisms, including fungi and bacteria. These bacteria are ubiquitous in the environment. Microbial growth on textiles can have adverse effects on both the fabric and the individual using it. The repercussions consist of the development of unpleasant odors, stains, and discoloration in the fabric, a decrease in fabric durability, and a higher likelihood of contamination. Therefore, it is highly important to inhibit the proliferation of microorganisms on fabrics while they are being used or stored.

Consumers' need for clean clothing has produced a significant demand for antimicrobial textile. Biocidal antimicrobial agents are those that kill bacteria and hinder the development of microorganisms, hence preventing odor generation. They are also known as biostatic agents [4, 5]. As a result, it is vital to discover antimicrobial agents with the least impact on human health and the environment. Plant-based antimicrobial substances are more ecologically friendly, safe, and non-toxic than synthetic chemicals, and they suppress bacterial infections. Most botanical extracts consist of bioactive chemicals. One of the most ancient medicine practices with fundamental principle which are developed in India, called as Ayurveda. In India, there are several plants species with medicinal properties [6]. *Basella alba* is a fast grown leafy vegetable plant with excellent medicinal properties which is cultivated worldwide [7]. The Basellaceae family includes *Basella alba*. Wine spinach, Malabar spinach, Indian spinach, and Ceylon spinach are some other names for it. The plant's aerial parts, including its leaves and stem, are utilized as edible plants or vegetables in various parts of the world.

The flavorful leaves and stems are used as a vegetable in soups, salads, stir-fries, and as a pot herb in stews [8]. *B. alba* leaves have a greater concentration of terpenoid and alkaloid compounds [9, 10], it is useful in the management of inflammatory diseases like diabetes mellitus, atherosclerosis, stroke, Alzheimer's disease, and heart disease. In Africa, Asia, and the West Indies, spreads widely and grows approximately 5 to 10 meters tall, leave range from 4 to 10 cm in length [11, 12]. *Jacaranda mimosifolia* is Pioneer tree, belong to Bignoniaceae family. *J. mimosifolia* grows in tropical region and subtropics of the world [13]. *J. mimosifolia* is cluster of beautiful foliage blue tubular flowers which commonly known as blue trumpet tree [14]. *Jacaranda mimosifolia* showed presence of alkaloids, flavonoids, phenols, saponins and tannins [15]. *J. mimosifolia* barks has been used in treatment of wound and skin ailments, hypertension, blood purification, eczema, fungal infections and traditional healers [16, 17]. *Moringa oleifera* Lam. is evergreen or deciduous tree, fast growing upto 10 to 12m height. It is alternatively referred to as the miracle tree, drumstick, tree for life, and horse radish tree [18]. *Moringa* is a deciduous herb that belongs to the Moringaceae family. It is native to the sub-Himalayan regions of India, Pakistan, Afghanistan, and Bangladesh [19, 20]. It is known for its nutritional properties. The crude methanolic extract of moringa leaves was shown to include phytochemicals such as alkaloids, flavonoids, tannins, polysaccharides, and saponins [21]. *M. oleifera* is frequently employed in Ayurvedic medicine to address cancer, malaria, typhoid fever, and joint pain [22]. Additionally, it provides assistance to mothers who are breastfeeding and enhances the production of milk after childbirth [23]. Literature demonstrates that these three medicinal plants are utilized in both traditional and modern therapy settings [24, 25 & 26]. The objective of this study is to evaluate the phytochemical composition and antibacterial properties of the extracts. The antibacterial properties of extracts from *Basella alba*, *Jacaranda mimosifolia* D. Don, and *Moringa oleifera* Lam. were tested on bamboo fabric.

2. Review of Literature

In the review article "Antibacterial Potential of Bamboo Extracts: A Comprehensive Review" [27], the authors provide a thorough examination of the antibacterial properties of bamboo extracts. They elucidate the efficacy of bamboo extracts against a broad spectrum of bacterial strains and delve into the underlying mechanisms contributing to their antibacterial activity. By analyzing the presence of bioactive compounds within bamboo extracts and their interactions with bacterial cells, the authors shed light on the multifaceted nature of bamboo's antibacterial potential. Furthermore, they explore potential applications of bamboo extracts across diverse domains, including medicine, personal care, and environmental health, underscoring the versatility and significance of bamboo as a natural antibacterial agent.

In the study "Exploring Medicinal Plants for Antibacterial Activity: A Systematic Review" [28], researchers systematically assess the antibacterial activity of various medicinal plants, including bamboo, synthesizing findings from multiple studies. Through this comprehensive analysis, the authors underscore the effectiveness of plant-derived compounds against pathogenic bacteria and elucidate their mechanisms of action. Moreover, they emphasize the importance of plant-based antibacterial agents as viable alternatives to conventional antibiotics, particularly in the context of combating antibiotic resistance. This systematic review contributes valuable insights into the potential of plant-derived compounds, including those derived from bamboo, in addressing global health challenges associated with bacterial infections.

Similarly, in the review article "A Review of Plant-Derived Compounds with Antibacterial Properties for Biomedical Applications" [29], the authors offer a comprehensive overview of plant-derived compounds with

antibacterial properties and their biomedical significance. By examining the diverse array of plant sources and their bioactive constituents, the authors underscore the rich reservoir of antibacterial agents present in nature, including those found in bamboo. Through a critical evaluation of existing literature, they highlight the potential biomedical applications of plant-derived antibacterial compounds, ranging from pharmaceuticals to personal care products. Overall, this review underscores the importance of harnessing the antibacterial potential of plants, such as bamboo, for the development of novel therapeutic interventions and biomedical innovations.

2.1 Research Gap

An area of research that has not been extensively studied in the realm of antibacterial capabilities of bamboo is the investigation of synergistic interactions among its bioactive chemicals. This gap was pointed out by [30]. Although there have been studies on the antibacterial effects of some chemicals, such as flavonoids or phenolic acids, there is a lack of study on how these compounds interact with each other and with bacterial targets to either enhance or inhibit antibacterial activity. [31] Similarly acknowledged this lack of understanding in their examination of antibacterial compounds originating from plants. Examining the combined impact of several bioactive components present in bamboo extracts could yield significant knowledge for enhancing antibacterial compositions and devising more potent remedies for bacterial illnesses. This research should also investigate the potential influence of these products on the development of microbial resistance, as indicated by the findings of [32]. By exploring new possibilities, we could potentially able to make contributions to the development of novel antibacterial properties to textiles produced from plant extracts. These textiles are would possess higher medicinal properties and be more ecologically friendly.

3. Materials and Methods

3.1 Materials

Basella alba, *Jacaranda mimosifolia* D. Don, and *Moringa oleifera* Lam. were sourced from several places in the hilly area of Salem, Tamil Nadu, for the study. The plant specimens were identified and verified by the Botanical Survey of India, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu. Plants were chosen for their therapeutic and pharmacological characteristics as described in the literature. The taxonomy of the chosen plants listed in Table 1 is shown alongside their corresponding photos in Figure 1. The medicinal herbs are labelled as a, b, and c. The fabric material used in this study is a 180 GSM bamboo fabric with a dobby weave. Figure 2 shows the corresponding image.

Table 1: Taxonomical of medicinal plants

Order	Family	Genus	Species	Common name
Caryophyllales	Basellaceae Raf.	Basella L.	Basella alba	Indian spinach
Scrophulariales	Bignoniceae	Jacaranda Juss.	Jacaranda mimosifolia D. Don	Pioneer tree
Capparales	Moringaceae Martinov	Moringa Adans.	Moringaoleifera Lam.	Drumstick tree

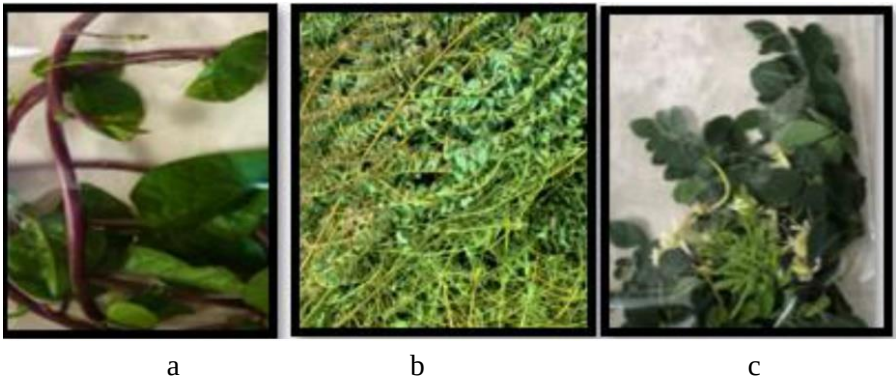


Figure 1: Basella alba (a), Jacaranda mimosifolia D. Don (b), Moringa oleifera Lam. (c)



Figure 2: Bamboo Fabric

3.2 Methodology

3.2.1 Solvent methanol extraction

The plant's leaves underwent a process of purification with distilled water, followed by exposure to a temperature of 50°C in an oven for around three hours. Subsequently, they were fragmented into tiny particles and further pulverized into a fine powder utilizing a commercial grinder. The Soxhlet device is a conventional extraction technique that utilizes an infusion-based method. For the extraction process, 100mg of powdered material was poured into a thimble and then extracted in a Soxhlet extractor using multiple solvents. The bag was placed into the gadget. During the extraction process, the methanol solvent was heated, causing it to evaporate and collect in a separate compartment called a thimble. It was then condensed and released into the condenser, which is placed on top. This process is iterated until the syphon arm completely transfers the liquid into the bottom flask, and then it recommences. The collected liquids were concentrated and desiccated at reduced pressure. The desiccated extracts were preserved in sterilized tiny containers at a temperature of 4°C for future utilization [33].

4. Phytochemical screening of extract

4.1 Presence of Alkaloids [34]

4.1.1 Mayer's test

To detect the presence of alkaloids, gently add drops of Mayer's reagent to 2 ml of extract using the test tube's side. A white or creamy precipitate will appear.

4.2 Presence of Flavonoids Test [35]

4.2.1 Alkaline reagent Test

There is no text provided. A total of 5 mL of extract was mixed with 2 mL of distilled water, followed by the addition of 0.15 mL of a 5% NaNO₂ solution. After a duration of six minutes, a volume of 0.15 mL of a solution containing 10% aluminum chloride was introduced and left undisturbed for an additional six minutes. Subsequently, a volume of 2 mL of a solution containing 4% sodium hydroxide was added to the combination. The mixture was rapidly diluted with distilled water and then left to incubate at room temperature for 15 minutes. The presence of flavonoids is indicated by the appearance of a pink hue.

4.3 Presence of Terpenoids Test [36]

4.3.1 Salkowski Test

C₄H₆O₃ and concentrated H₂SO₄ were introduced into a 2ml sample of plant material extract. The presence of terpenoids causes the formation of blue-green rings in the formula.

4.4 Presence of Phenolic Test [37]

4.4.1 Ferric chloride Test

Combine 1ml of the extract with 5ml of distilled water in a test tube for the phenol test. The solution exhibited strong oscillations and displayed a consistent, enduring foam. When three drops of phenol are mixed with froth and vigorously shaken, they produce a lasting blue colour.

4.5 Presence of Tannin Test [38]

4.5.1 Ferric chloride Test:

10 milliliters of distilled water mixed with 1 milliliter of extract. Combining 2 ml of filtrate with 2 ml of FeCl₃

after filtering the mixture. A blue-black precipitate formed, indicating the presence of tannins.

5. Antibacterial screening of plants extractions treated on bamboo fabric

5.1 Assessment of Antibacterial activity (EN ISO 20645)

Over the past few decades, there has been an increasing worldwide fascination with various herbal plants due to their inherent antibacterial capabilities [39]. Pathogenic diseases caused by bacteria, viruses, fungi, and parasites continue to pose a significant threat [40]. Ensuring a hygienic living environment is crucial for effectively controlling germs [41]. The plant crude extract was prepared from three samples and tested for antibacterial activity using the EN ISO 20645 test method. The test specimens, in the form of swatches, were precisely cut into pieces with a diameter of 20mm. These pieces were then subjected to testing using two standard bacterial cultures. Both test microorganisms maintained in nutrient agar slants. Both test bacteria were cultivated on Nutrient Agar slants in a microbiology laboratory. Table 2 displays the media composition of Nutrient broth and Mueller-Hinton agar composition [42]. The inoculation broth tubes were incubated at 37 degrees Celsius for 12 to 24 hours until bacterial growth became turbid. Each test bacterial culture (*Escherichia coli* and *Staphylococcus aureus*) was placed onto the Mueller-Hinton agar (MHA) plate and the central region of the petri dish using a sterile 4mm inoculating loop by swabbing the surface.

Table 2: Nutrient Broth and Mueller-Hinton agar Composition

Nutrient Broth Composition	Media Composition	g/L
	Peptone	5.0
	Yeast extract	5.0
	Beef extract	3.0
	Sodium chloride	5.0
	pH	7.0 ± 0.2
	Distilled water	1000ml
Mueller-Hinton agar Composition	Media Composition	g/L
	Acid hydrolysate of Casein	17.5
	Starch	1.5
	Agar	20.0
	Sodium chloride	5.0
	pH	7.0 ± 0.2
	Distilled water	1000ml

Every test organism was given a separate Mueller-Hinton agar plate within a sterile area. Following the collection of test microorganisms, the test fabric swatches (including treated and untreated control fabrics) were placed on opposite sides of the MHA plates. The identical procedure was applied to all test samples. The plates containing test swatches were placed in a regular incubator and kept at a temperature of 37°C for a duration of 12 to 24 hours. After the specified incubation period, all test plates were examined for a clearly visible area where the growth of microorganisms was prevented around the treated textiles. The diameter of the zone of inhibition surrounding each fabric sample was quantified in millimeters (mm) and then recorded.

5.2 Method of finishing on fabric

The chosen fabric material was immersed in a standard solution of fresh water for a duration of 20 minutes. The laundered fabrics underwent a thorough rinsing process in flowing water to remove any surface dirt and pollutants. All of the material was delicately compressed by hand and air-dried at ambient temperature. A 1% (10g/L) solution of sodium lauryl sulphate, a non-ionic detergent, was employed to remove any surplus starchy components from the surface of the fabric. Padding was done with 80% wet pick up, at neutral pH, and at room temperature using a solution that contained 1% extract, 1% crosslinking agent (citric acid), and 0.5% wetting agent. After that, it was dried for five minutes at 80°C and cured for two minutes at 120°C. The samples underwent UV disinfection in a controlled airflow chamber for a duration of 30 minutes, followed by storage in a sterile environment for subsequent investigation. Figure 3 contains the relevant photographs of the treated fabric that was retrieved.

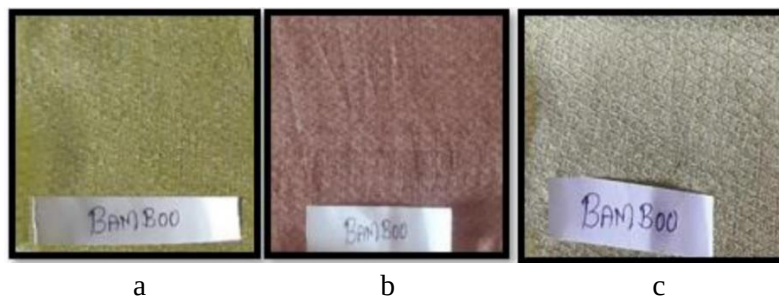


Figure 3: Plant extractions treated on bamboo fabric

6. Results and discussion

Table 3 displays the results of the phytochemical analysis conducted on *Basella alba*, *Jacaranda Mimosifolia* D. Don, and *Moringa oleifera* Lam. Plants possess bioactive compounds such as alkaloids, terpenoids, steroids, phenols, and flavonoids. *Basella alba* extracts contain alkaloids, flavonoids, terpenoids, and tannin. Flavonoids and phenols were detected in the extracts of *Jacaranda mimosifolia*. Alkaloids, flavonoids, and phenols were detected in extracts of *Moringa oleifera* Lam, suggesting the existence of bioactive constituents that exhibit medicinal plant properties.

Table 3: Results of phytochemical screening test

Compound	Test	<i>Basella alba</i>	<i>Jacaranda mimosifolia</i> D. Don	<i>Moringa oleifera</i> Lam.
Alkaloids	Mayer's test	+	-	+
Flavonoids	Alkaline reagent Test	+	+	+
Terpenoids	Salkowski Test	+	-	-
Phenol	Ferric chloride Test	-	+	+
Tannin	Ferric chloride Test	+	-	-

*+ = positive to color test, *- = negative to color test

6.1 Antibacterial assay

The antibacterial characteristics of the methanol extract of the plants were tested, and it was found to have the highest antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* compared to the other two solvent extracts. Extracts from *Basella alba* showed inhibitory zones measuring approximately 20mm and 16mm against *Escherichia coli* and *Staphylococcus aureus*, respectively. Extracts from *J. Mimosifolia* displayed inhibitory zones of about 19mm and 18mm against the same bacteria. *M. oleifera* extracts demonstrated inhibitory zones of approximately 18mm and 15mm against *Escherichia coli* and *Staphylococcus aureus*, respectively. These results are shown in Table 4, Figure 4 and 5 were present the outcomes of the antibacterial screening test conducted on the raw extract of several plants against the examined microorganism. The solvent extract derived from the medicinal plant shown significant efficacy against *Escherichia coli* and *Staphylococcus aureus*. The antibacterial capabilities of medicinal plants are most potent in the methanolic extract, surpassing the effectiveness of acetone and ethanol. The study provides evidence that the plant leaves possess antibacterial properties.

Table 4: Antibacterial Screening of *Basella alba*, *J. Mimosifolia* and *M. oleifera* against *Escherichia coli* and *S. aureus*

Medicinal plants	Zone of Inhibition against <i>E. coli</i> (in mm)			Zone of Inhibition against <i>S. aureus</i> (in mm)		
	Petroleum ether (PE)	Methanol (M)	Acetone (A)	Petroleum ether (PE)	Methanol (M)	Acetone (A)
<i>Basella alba</i>	11	20	0	12	16	0
<i>J. Mimosifolia</i>	0	19	13	0	18	10
<i>M. oleifera</i>	14	18	0	12	15	0

The reason for the effective antibacterial activity of herbal extract was keen to identify from the literature source

available. The relevance of phytochemical components and other biological substances of *Basella alba*, *J. mimosifolia* and *M. oleifera* that are attributing to antibacterial abilities, antioxidant properties, anticancer properties, etc. were noted in several studies.

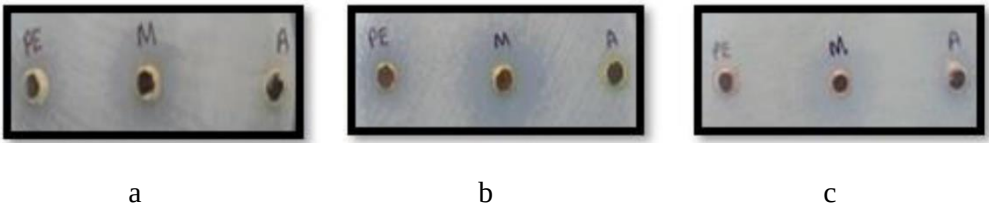


Figure 4. Antibacterial Screening of individual plants against *Escherichia coli*

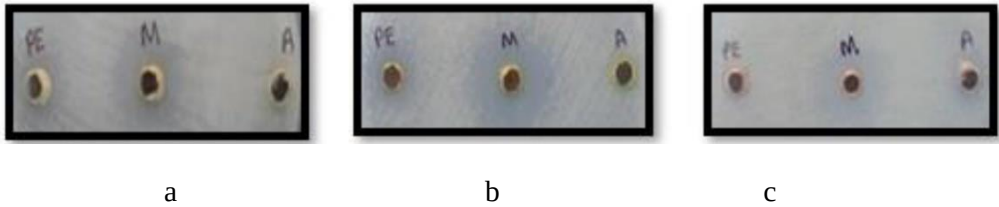


Figure 5: Antibacterial screening of individual plants against *Staphylococcus aureus*

The study showed a substantial reduction in the growth of both Gram-Negative and Gram-Positive bacteria, resulting in the development of dependable, economical plant products and potential ingredients for wide-ranging antibacterial drugs. The researchers identified several secondary metabolites, including as tannins, terpenoids, alkaloids, and flavonoids, all of which had strong antibacterial properties.

6.2 Antibacterial activity of plant extract treated on bamboo fabrics

The plant extracts applied to fabric samples exhibited significant antibacterial inhibitory zones as detailed in Table 5. Examined samples of treated fabric (F) and untreated fabric (UF) for microbial presence. The *Basella alba* extract applied to bamboo fabric exhibited inhibitory zones measuring approximately 26mm and 25mm against *Escherichia coli* and *Staphylococcus aureus*, respectively. The fabric treated with *Jacaranda mimosifolia* D. Don extract exhibited inhibitory zones measuring around 26mm and 24mm, while the fabric treated with *Moringa oleifera* Lam. showed antibacterial activity with zones of 28mm and 25mm against the test microorganisms.

Table 5: Antibacterial activity of plants extraction treated on bamboo fabric

Selected Medicinal plants	Zone of Inhibition (in mm)	
	<i>Escherichia coli</i>	<i>Staphylococcus aureus</i>
<i>Basella alba</i>	26	25
<i>Jacaranda mimosifolia</i> D. Don	26	24
<i>Moringa oleifera</i> Lam.	28	25

At a societal level, the investigation into utilizing medicinal plant extracts as natural dyes and antibacterial agents on bamboo cloth offers a sustainable solution to the environmental concerns associated with synthetic dyes. By promoting eco-friendly textile production methods, the research contributes to reducing chemical pollution and environmental degradation, aligning with global efforts towards sustainability. Furthermore, the development of antimicrobial bamboo fabrics addresses consumer demands for safer and healthier textile options, potentially mitigating the risk of bacterial infections and improving overall well-being. For the research community, this study represents a valuable contribution to the field of textile science and pharmacology. By analyzing the phytochemical composition and antimicrobial properties of medicinal plant extracts on bamboo fabric, researchers gain insights into novel applications of natural compounds in textile production. This interdisciplinary approach fosters collaboration between textile scientists, pharmacologists, and microbiologists, leading to a deeper understanding of the potential therapeutic benefits of medicinal plants in textile applications. Additionally, the study opens up avenues for further research into biomedical textiles and antimicrobial fabrics, driving innovation and knowledge advancement in these fields. Within academia, the findings of this research enrich the

existing body of knowledge on natural dyeing techniques and sustainable textile production methods. By documenting the phytochemical analysis, antioxidant properties, and antibacterial effects of medicinal plant extracts on bamboo fabric, the study contributes to academic discourse on environmentally friendly textile innovations. Moreover, it underscores the importance of interdisciplinary research approaches in addressing complex societal challenges, such as environmental sustainability and public health. As such, the research serves as a catalyst for future studies exploring the intersection of textile science, pharmacology, and microbiology, ultimately driving progress and innovation in these interconnected fields.

7. Conclusion

The study focuses on the rise of natural dyeing in the textile sector and evaluates the antibacterial properties of medicinal plants such *Basella alba*, *Jacaranda mimosifolia* D. Don, and *Moringa oleifera* Lam. These plant extracts are applied to bamboo fabric. *Basella alba* leaves were found to contain alkaloids, flavonoids, terpenoids, and tannins through phytochemical examination. Flavonoids and phenols were identified in the foliage of *Jacaranda mimosifolia* D. Don. The leaves of *Moringa oleifera* Lam were discovered to contain alkaloids, flavonoids, and phenols. The medicinal plants demonstrate significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*. The study suggests that cloth, which has been treated with plant extract, has the potential to be transformed into biomedical and home textile goods that are standardized, safe, and cost-effective.

7.1 Limitation of the study

The limitations of this study encompass several aspects. Firstly, the research has a narrow focus on only three specific medicinal plants (*Basella alba*, *Jacaranda mimosifolia* D. Don, and *Moringa oleifera* Lam.), which may not fully represent the diversity of plant-based natural dyes and antibacterial agents available in nature. Consequently, the findings may not be generalizable to other medicinal plants with potentially different chemical compositions and properties. Secondly, the study's reliance on a limited range of solvents (acetate, methanol, and petroleum ether) for extracting bioactive compounds from the medicinal plant leaves may have overlooked alternative extraction methods that could yield different results. By investigating alternative solvents or extraction methods, a more thorough comprehension of the bioactive chemicals found in plants and their potential uses in textile manufacturing could be achieved. In addition, the study evaluated the antioxidant and antibacterial characteristics of the medicinal plant extracts against specific microorganisms (*Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, and *Candida tropicalis*). However, it did not examine their effectiveness against a wider range of pathogens or take into account potential differences in antimicrobial activity depending on geographical location, plant growth conditions, or seasonal variations. Finally, the study's findings and conclusions are based on laboratory experiments and may not fully reflect real-world conditions or practical challenges associated with scaling up the production of antimicrobial bamboo fabrics using medicinal plant extracts. Further research involving pilot-scale production and field trials would be necessary to assess the feasibility, scalability, and economic viability of implementing such processes in industrial textile manufacturing.

7.2 Conflict of interest

No conflict of interest

7.3 Funding source

Authors report no financial support from any funding agency or institution

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