Herbal-Infused Silver Nanoparticle Functionalized Cotton Masks for Enhanced Antimicrobial Protection

Arivumani Ravanan[1], Palanisamy[1]

[1] Department of Mechanical Engineering, KIT – Kalaiganrkarunanidhi Institute of Technology, Coimbatore - 641402, India.

ABSTRACT

The need for more effective personal protective equipment has arisen as a result of the increasing demand for masks during global health emergencies. In light of this, this paper seeks to describe the development of an antimicrobial mask that is both environmentally friendly and effective. The preparation of herbal extracts from Ocimum tenuiflorum, Coleus amboinicus, Mentha arvensis, Salvia rosmarinus, and Curcuma longa involved the use of solvent extraction techniques. The identification of the phytochemicals contained within the herbal extract was accomplished via phytochemical screening. The green synthesis process utilized the herbal extracts as precursors to the formation of the silver nanoparticles (AgNPs). The characterization of AgNPs involved the use of UV-Visible Spectroscopy and particle size measurement. The antimicrobial potential of the herbal extracts and AgNPs was assessed using agar well diffusion and disk diffusion techniques against Gram-positive and Gram-negative bacteria. The functionalization of 100% cotton fabric using the pad-dry-cure method was undertaken. The results revealed high zones of inhibition, which indicated enhanced antibacterial activity when compared with untreated fabrics.

Keywords: Herbal extracts, Silver nanoparticles (AgNPs), Antimicrobial face mask, Green synthesis, Cotton functionalization, Pad–dry–cure method, Phytochemical analysis, Antibacterial activity, Sustainable textiles

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1. Introduction

The outbreak of infectious diseases and especially the current COVID-19 pandemic has shown the crucial need for personal protective equipment (PPE) in reducing the transmission of diseases. Among many forms of protective gear, face masks have proven to be the most important preventive barrier against infectious agents by lowering the likelihood of airborne respiratory infections significantly (Howard et al., 2021). Nevertheless, there have been numerous environmental issues associated with the extensive application of conventional single-use masks because of the non-degradable materials used to make them, which results in the generation of medical waste (Aragaw, 2020). Moreover, the usage of such masks increases the probability of secondary infection from the accumulated microorganisms on the surface of the mask (Chua et al., 2020).

In order to cope with this situation, several studies have recently concentrated their efforts towards producing reusable and functional masks that have both protective and antimicrobial functionalities. In relation to this, plant extract-based materials have become more popular for their inherent ability to have antimicrobial, antiviral, and antioxidant functions (Bakkali et al., 2008). The use of medicinal plants is well known since ancient times, and the World Health Organization has indicated that many people around the world are dependent upon plants as sources of medication for their basic health care requirements (WHO, 2019). Medicinal plants contain various active agents such as flavonoids, alkaloids, tannins, and phenolic acids that exhibit potent antimicrobial functions against different pathogens (Cowan, 1999).

Of several medicinal plants, those which include Tulsi (Ocimum tenuiflorum), Indian borage (Coleus amboinicus), mint (Mentha arvensis), rosemary (Salvia rosmarinus), and turmeric (Curcuma longa) are among those plants whose medicinal applications have been well documented in numerous scientific studies (Prakash & Gupta, 2005; Díaz et al., 2016). These medicinal plants possess essential oils and phytochemicals, which exhibit a significant degree of antimicrobial activity in both bactericidal and virucidal capacities and thus can be used in the production of antimicrobial fabrics. For example, curcumin, the active chemical in turmeric, interferes with the structure of microbial membranes (Gupta et al., 2013).

Concurrently, the domain of nanotechnology has been developing novel ways of improving the efficacy of antimicrobials by employing metallic nanoparticles. These include the application of silver nanoparticles (AgNPs), which have gained a lot of interest as they possess wide-spectrum antimicrobial effects, large surface-to-volume ratio, and structural destruction of microorganism cells (Rai et al., 2009). There is no single mode of action for AgNPs; on the contrary, they utilize a few different techniques, such as creation of reactive oxygen species, protein-DNA binding, and disruption of cell membrane integrity, minimizing the development of antimicrobial resistance (Morones et al., 2005). Another innovative method involves the utilization of plant extracts as green nanoparticles, providing an ecological and cheap alternative to traditional synthesis because biomolecules from plants can serve as both reducers and stabilizers (Iravani, 2011).

Combination of herbal extracts and silver nanoparticles has been proposed as a synergy that enhances anti-microbial properties while reducing the toxicity risk. These hybrid combinations have demonstrated their effectiveness especially in biomedicine and textiles for antimicrobial surface coatings and functionalized materials (Shankar et al., 2004). Cotton textile has been selected because it is biodegradable, porous, breathable, and most commonly used in various applications in textiles. Antimicrobial agent delivery to cotton material can be accomplished through the pad-dry-cure process.

There is a clear need for research combining the two factors, i.e., herb-derived extract along with nanotechnology in the development of reusable face masks. While most of the recent research has been done in one of the two fields, very few studies have attempted to integrate both for better results. Moreover, the development of techniques for creating masks is itself an area where further research is needed to optimize both functionality and comfort of the end product.

Consequently, the current research seeks to formulate and assess the efficacy of an innovative herbal-infused silver nanoparticle-enriched cotton face mask with enhanced antibacterial characteristics. The study is designed to extract plant-based bioactive compounds, synthesize AgNPs via environmentally friendly methods, and apply the nanoparticles on cotton fibers following a specific finishing procedure. The antimicrobial efficiency of the newly synthesized material is rigorously evaluated by testing its effectiveness against a range of bacterial pathogens.

2. Methodology

The research method employed in this study emphasizes the detailed analysis of plant extracts, preparation of AgNPs through green synthesis techniques, and their effectiveness against various microorganisms before using them for textile applications. The approach was selected with an emphasis on repeatability, reliability, and demarcation from the process of fabrication.

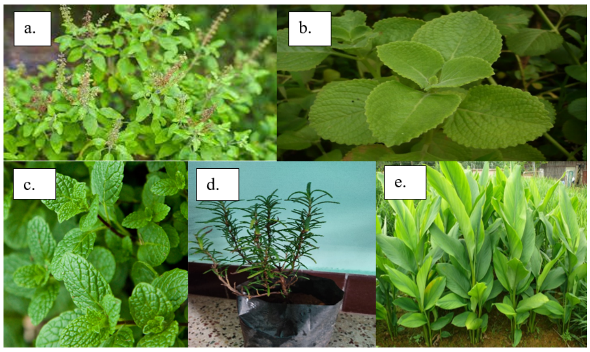

Fig. 1 Herbs collected for experiments. a. Basil b. Oregano c. Peppermint d. Rosemary e. Turmeric

2.1 Collection and Preparation of Herbal Materials

Collection of fresh samples of plants such as Ocimum tenuiflorum, Coleus amboinicus, Mentha arvensis, Salvia rosmarinus, and Curcuma longa was done in the Coimbatore district, Tamil Nadu, India. Authentication of plant samples was achieved through the use of standard botanical practices. Samples collected were washed to ensure that any dirt was removed and air-dried at room temperature for one week to protect bioactive ingredients in the sample. After drying, samples were grounded to powder form and stored in tightly sealed containers.

2.2 Solvent Extraction of Herbal Compounds

The plant samples that were ground into fine powder form underwent solvent extraction using a Soxhlet apparatus to obtain active ingredients. Three solvents—distilled water, ethanol, and methanol—were used depending on their polarity. This ensured effective extraction of the active components. In the case of the distilled water and ethanol/methanol extractions, 10 grams of the plant material was mixed with 100 milliliters of distilled water/ethanol/methanol. The extractions were done at controlled temperatures of around 100 °C and 60-70 °C, respectively.

2.3 Phytochemical Screening

Phytochemical qualitative analysis was performed to establish the presence of biologically active secondary metabolites. Conventional procedures were used for testing for secondary metabolites like alkaloids, flavonoids, phenols, tannins, saponins, glycosides, proteins, and phytosterols. Presence/absence of these metabolites was noted on the basis of their distinct color development or precipitation with the help of conventional chemical tests like Wagner test, ferric chloride test, Fehling's test, and Ninhydrin test.

2.4 Evaluation of Antibacterial Activity of Herbal Extracts

Anti-microbial effects of the herbal extracts obtained were tested on selective bacteria such as Staphylococcus aureus, Escherichia coli, and Klebsiella pneumoniae.

2.4.1 Agar Well Diffusion Method

Sterile agar plates were first prepared, and bacterial cultures were inoculated in the plates using swabbing method. Wells were made in the agar plate using sterile corn borers. The herbal extracts were then poured into these wells, and the plates were left incubated at 37° Celsius for 24 hours.

2.4.2 Disk Diffusion Method

Sterile filter paper discs saturated with plant extract were applied to agar plates containing bacterial cultures. The plates were incubated at 37°C for 24 hours, after which the zone of inhibition was determined by measuring its diameter.

2.5 Determination of Minimum Inhibitory Concentration (MIC)

The determination of MIC of the herbal extract was carried out using broth dilution assay technique. Serial dilutions of the extracts were made in the microtitre plate and then bacterial inoculums were added into each well. This procedure was carried out at 37 degrees Centigrade for 24 hours after which growth was quantified based on turbidity. Inhibition of bacterial growth was quantitatively measured by spectrophotometry.

2.6 Green Synthesis of Silver Nanoparticles

The green synthesis of silver nanoparticles was achieved by making use of the extracted herbs as reducing and stabilizing agents. An equal amount of the selected herbal extracts was mixed together, and then the silver nitrate solution was added. In order to synthesize AgNPs, it was made sure that there were no sources of light near the reaction mixture, resulting in a color change.

2.7 Characterization of Silver Nanoparticles

AgNPs formed through synthesis were characterized to establish their successful synthesis and physicochemical characteristics. Surface plasmon resonance peaks were detected by the use of UV-VIS spectroscopy to verify the successful synthesis of nanoparticles. Particle size analysis was conducted using a particle size analyzer while surface morphological characteristics were examined by SEM.

2.8 Antibacterial Activity of Silver Nanoparticles

The anti-microbial effect of the prepared AgNPs was determined by performing the agar well diffusion assay on some chosen strains of bacteria. Various concentrations of AgNPs were used, together with the positive control (antibiotics) and negative control (distilled water). The zones of inhibition were later measured to determine the improved antibacterial effects of the nanoparticle solution samples.

3. System Design and Development

The design and development of the proposed system will entail the creation of the AgNP impregnated face mask made from a herbal solution impregnated cotton fabric. The following discussion concentrates on the process of implementing the mask design.

3.1 Material Selection

For fabric, 100% cotton fabric was chosen due to its natural degradation, breathable nature, and suitability for chemical finishing. Cotton fabric can absorb water well and is comfortable to wear for long periods of time, which makes it ideal for face masks. Cotton fabric of high quality in nonwoven or woven form was acquired from a reputable textile company.

3.2 Preparation of Functional Finishing Solution

The antimicrobial finish was developed using the AgNPs produced via herbal synthesis. The composition of this formulation consisted of Herbal extract-mediated silver nanoparticle solution, Silver nitrate ($AgNO_3$) used as a precursor for better binding (if needed), Citric acid used as a binder/cross-linking agent, and Softener to make the fabric soft. These materials were combined in specific quantities to create a mixture. The use of binder helped in ensuring that the nanoparticles adhere well to the fabric, while the softener made the fabric more flexible.

3.3 Fabric Pretreatment

Before the process of functionalizing the material, it was prepared by washing it to ensure there were no residues present such as waxes, oils, or dust particles that would inhibit the ability for chemicals to absorb into the cloth. Wetting agents were used on the fabric, which helped to make it more wettable.

3.4 Pad–Dry–Cure Process

The functionalization of cotton fabric with the herbal AgNP solution was carried out using the pad–

dry–cure technique, a widely used industrial textile finishing method.

3.4.1 Padding

The treated cotton cloth was dipped into the prepared finishing bath for a definite period to make sure that it is totally saturated. The soaked cloth was padded using the padding mangle with the pressure maintained around 2 kg/cm² and speed. Nearly 100% wet pickup was maintained for proper coating of the cloth.

3.4.2 Drying

The padded fabric was subjected to drying at a controlled temperature of around 70°C. This step removed excess moisture and facilitated preliminary fixation of the antimicrobial agents onto the fibre surface.

3.4.3 Curing

The dried fabric was then cured at an elevated temperature (approximately 150–160°C) for a specified duration. Curing enabled crosslinking between the cotton fibres and the finishing agents, ensuring durability of the antimicrobial coating even after repeated usage and washing.

3.5 Fabrication of Face Mask

The treated cotton fabric was used to fabricate a triple-layered face mask to enhance filtration efficiency and protection. The mask design included:

- **Outer layer:** AgNP-functionalized cotton layer for antimicrobial protection
- **Middle layer:** Additional cotton or filter layer for enhanced filtration
- **Inner layer:** soft cotton layer for user comfort and moisture absorption

The layers were cut into standard mask dimensions and stitched using a sewing machine, ensuring proper sealing at the edges to minimize air leakage. Elastic ear loops and a nose clip were incorporated to provide a secure and comfortable fit.

3.6 Design Considerations

The mask design was developed considering multiple functional requirements:

- **Antimicrobial efficiency:** Achieved through uniform AgNP coating
- **Breathability:** Maintained by using cotton fabric with controlled porosity
- **Reusability:** Ensured through durable chemical finishing
- **User comfort:** Enhanced through soft inner layers and ergonomic design

4. Results and Discussion

The results obtained from phytochemical analysis, antimicrobial testing, nanoparticle characterization, and fabric performance evaluation are presented and discussed in this section. The findings demonstrate the effectiveness of herbal extracts and their synergistic interaction with silver nanoparticles (AgNPs) in enhancing antimicrobial properties.

4.1 Phytochemical Analysis

Qualitative phytochemical screening confirmed the presence of key bioactive compounds in all selected herbal extracts. Compounds such as flavonoids, phenols, tannins, alkaloids, and saponins were predominantly observed, which are known for their antimicrobial activity.

Table 1. Phytochemical Screening of Herbal Extracts

Phytochemical Compound	Basil	Oregano	Peppermint	Rosemary	Turmeric
Alkaloids	+	+	+	+	+
Flavonoids	+	+	+	+	+
Phenols	+	+	+	+	+
Tannins	+	+	+	+	+
Saponins	+	+	+	+	-
Glycosides	+	+	+	+	+

The presence of these phytochemicals supports the antimicrobial potential of the extracts, as reported in earlier studies (Cowan, 1999). Phenolic compounds and flavonoids are particularly effective due to their ability to disrupt microbial cell membranes and inhibit enzymatic activity.

4.2 Antibacterial Activity of Herbal Extracts

The antibacterial activity of herbal extracts was evaluated using agar well diffusion and disk diffusion methods. The results showed varying degrees of inhibition against both Gram-positive and Gram-negative bacteria.

Table 2. Zone of Inhibition (mm) for Herbal Extracts

Extract	*S. aureus*	*E. coli*	*K. pneumoniae*

Basil	14	12	11
Oregano	16	13	12
Peppermint	13	11	10
Rosemary	15	12	11
Turmeric	17	14	13

Among the tested extracts, turmeric and oregano exhibited relatively higher antibacterial activity. The effectiveness against *Staphylococcus aureus* was generally higher than against Gram-negative bacteria, which may be attributed to the structural differences in bacterial cell walls (Rai et al., 2009).

4.3 Performance of Functionalized Cotton Fabric

The cotton fabric treated with herbal AgNPs demonstrated significant antimicrobial activity compared to untreated fabric.

Table 3. Antibacterial Activity of Fabric Samples

Fabric Type	***S. aureus* (mm)**	***K. pneumoniae* (mm)**
Untreated Cotton	0	0
Herbal Extract Treated	12	10
AgNP Functionalized Cotton	20	18

The results confirm that the pad–dry–cure method enabled effective deposition of antimicrobial agents onto the fabric. The AgNP-functionalized fabric exhibited superior antibacterial performance due to the combined effect of herbal bioactive compounds and nanoparticles.

Fig. 2 Herbal infused face mask with three coated layers of cloth

4.4 Discussion

In the current study, it is evident that there is a definite improvement in antimicrobial efficacy in the case of herbal extracts used along with AgNPs. Although the individual herbal extracts show moderate antibacterial efficacy, their combination with AgNPs shows a synergic response, thus leading to an increased bacterial inhibition efficiency. This is due to the dual action of the phytochemicals, whereby the metabolic activities of the bacteria are inhibited by the former and physical destruction of the microbes occurs via the latter.

Moreover, the success of applying the treatment solution on the fabric with the help of the PDC method makes this technique useful in terms of applicability in future. In addition to maintaining breathability, it provides improved protection against microbes. Hence, such functionalized fabrics could easily be employed in producing reusable face masks.

5. Conclusion

The results show that the present study was able to create a herbal extract-infused, silver nanoparticle (AgNP)-coated cotton face mask with better antibacterial properties. In this context, the selection of five medicinal plants, namely Ocimum tenuiflorum, Coleus amboinicus, Mentha arvensis, Salvia rosmarinus, and Curcuma longa, is seen to provide adequate bioactive compounds, which have been determined through phytochemical screening. These bioactive compounds contributed to the presence of intrinsic antibacterial properties. The preparation of AgNPs using herbal extracts is an efficient and environmentally-friendly process with good cost-effectiveness. The results obtained from characterization techniques suggest that the nanoparticles were produced in good yield with proper size and morphology that could be crucial for antimicrobial activity. The AgNPs have proven to possess significantly high levels of antibacterial activity compared with individual herbs, suggesting synergy between these particles. Moreover, the successful functionalization of cotton material through pad-dry-cure technique ensures effective coating and durability of the AgNPs. In the context of the antibacterial activity of the developed triple-layered face mask, it shows significantly higher performance compared with unmodified and modified herbal face mask. This indicates better efficacy of the mask to inhibit the growth of microorganisms while preserving the essential properties.

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