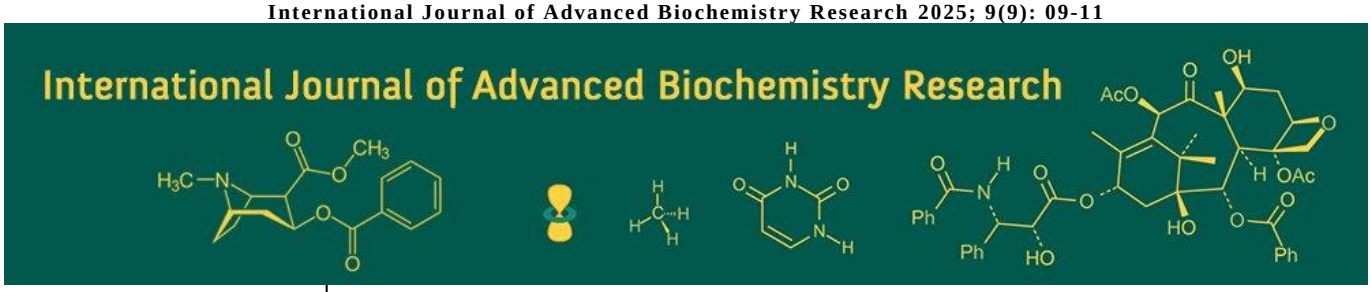

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Nisha Arya
Department of Apparel and Textile Science, College of Community Science, CCS Haryana Agricultural University, Hisar, Haryana, India

Kamla Malik
Department of Microbiology, College of Basic Science and Humanities, CCS Haryana Agricultural University, Hisar, Haryana, India

Arpita Grover
Amity University, Panvel, Mumbai, Maharashtra, India

Lalita Rani
Department of Apparel and Textile Science, College of Community Science, CCS Haryana Agricultural University, Hisar, Haryana, India

Neeta
Department of Apparel and Textile Science, College of Community Science, CCS Haryana Agricultural University, Hisar, Haryana, India

Corresponding Author:
Nisha Arya
Department of Apparel and Textile Science, College of Community Science, CCS Haryana Agricultural University, Hisar, Haryana, India

Wash durability of silver nanoparticle finished cotton fabric

Nisha Arya, Kamla Malik, Arpita Grover, Lalita Rani and Neeta

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Abstract
The present study focusses a green synthesis route by synthesizing silver nanoparticles using neem leaf extract and applying them on cotton fabric. The wash durability of the nano-finished fabrics on the basis of antimicrobial activity was carefully assessed up to 20 laundering cycles. Antimicrobial performance of the finished fabrics was tested against a range of pathogenic microorganisms, including *Pseudomonas aeruginosa* and *Escherichia coli* (Gram-negative bacteria), *Bacillus cereus* and *Staphylococcus aureus* (Gram-positive bacteria), and *Trichoderma* (unicellular fungi) using established test procedures. The nano-finished cotton fabric treated with silver nanoparticles synthesized from *neem* leaves extract demonstrated excellent wash durability even after 20 wash cycles i.e. 95.32 percent reduction in microbial growth for *P. aeruginosa*, 93.80 percent for *E. coli* (-ve bacteria), 94.91 percent for *S. aureus*, 95.43 percent for *B. cereus* (+ ve bacteria) and 92.80 percent for *Trichoderma* fungi. This thorough analysis not only shows the potential of neem-mediated AgNP finishes as environmentally friendly substitutes for traditional chemical treatments, but it also sheds light on their potential long-term application in household goods, medical textiles, and hygiene textiles.

Keywords: Green synthesis, silver nanoparticles, neem leaf extract, antimicrobial activity, cotton fabric finishing, wash durability

Introduction
The textile sector has experienced substantial changes in recent years, moving away from traditional manufacturing toward the creation of value-added items with improved features. 28.8.25 Synthetic compounds such as triclosan, quaternary ammonium salts, and metallic derivatives have long been used to impart antimicrobial properties to fabrics. While effective at first, their application is limited by drawbacks such as, environmental persistence, reduced performance after laundering, health-related toxicity and bioaccumulation risks (Perelshtein *et al*., 2008) [5]. Due to the global swing toward eco-friendly and sustainable solutions, researchers are focussing towards development of natural, renewable and environmentally safe alternatives (Ali *et al*., 2019) [2]. In this context, offers a means to strengthen both the effectiveness and durability of antimicrobial textile treatments.

Silver nanoparticles (AgNPs) are well recognized for broad-spectrum antimicrobial activity against bacteria, fungi, and certain viruses (Rai *et al*., 2009) [6]. Their large surface area enhances reactivity and interaction with microbial cells (Ahmed *et al*., 2016) [1]. However, their use in textiles is limited by poor wash durability, as nanoparticle leaching reduces long-term efficacy (Ali *et al*., 2019) [2]. To overcome drawbacks of chemical synthesis, eco-friendly "green" methods are being explored, utilizing biological agents such as microbes and plant extracts. Plant-derived phytochemicals—flavonoids, terpenoids, and phenolics—serve as natural reducing and stabilizing agents (Ahmed *et al*., 2016) [1]. Among these, neem (Azadirachta indica), rich in bioactive compounds and known for strong antimicrobial properties, shows promise for producing durable, sustainable AgNP-based fabric treatments (Biswas *et al*., 2002) [3].

Incorporating neem-derived silver nanoparticles (AgNPs) into cotton fabric offers a sustainable strategy that merges plant-based bioactivity with nanotechnology to improve antimicrobial resistance. While this eco-friendly approach enhances fabric protection, its effectiveness declines with repeated washing, limiting durability and cost efficiency (Ali *et al*., 2019) [2].

In this research, neem leaf extract was utilized for the green synthesis of silver nanoparticles, and wash durability of the fabric finished with nano particles was assessed up to 20 washing cycles using standardized methods. The outcomes not only confirm the promise of neem-mediated AgNP coatings as sustainable substitutes for chemical finishes but also indicate their potential applications in domestic textiles, medical fabrics, and hygiene-related products.

Methodology

Cotton fabric was treated with silver nanoparticles synthesized from neem leaf extract, and the durability of this nano-finishing was evaluated by examining its antimicrobial effectiveness against pathogenic microbes after washing.

Washing of Cotton Fabric Treated With Silver Nanoparticles

For washing the samples, 'Launder-o-meter' as per ISO: 6330-1984E standard test method was used. The samples of 10 x 2.5 cm size were cut from nano-finished fabric. A solution containing 4 g/l soap and 2 g/l sodium carbonate (Na_2CO_3) was prepared for washing. Standard soap and sodium carbonate were dissolved in water taking 1:20 MLR ratio. The solution was stirred for few minutes to make it completely homogenized and the fabric samples were put in the steel containers of the 'Launder-o-meter'. The containers were fastened inside the instrument and the lid was closed, further the samples were washed at 30 °C for 20 minutes. After washing, the samples were rinsed in lukewarm water and then air dried.

Assessment of Wash Durability of Nano Treated Cotton Fabric against Growth of Microorganisms

The washed samples were inoculated with the selected microorganisms. The microbial count (CFUs) of the washed and inoculated samples was determined quantitatively using AATCC-100 test method. The unwashed samples finished with herbal finish by pad dry cure method were taken as controlled samples. The efficacy of nanofinish was analysed against antimicrobial activity of pathogenic microorganisms i.e., *Pseudomonas aeruginosa*, *Escherichia coli* (-ve bacteria), *Staphylococcus aureus*, *Bacillus cereus* (+ ve bacteria) and *Trichoderma* fungi after 5, 10, 15 and 20 wash cycles using standard test method.

Results

Silver nanoparticles were synthesized from *neem* leaves extract and applied on cotton fabric. The antimicrobial activity of herbal finished cotton fabric was then assessed against pathogenic bacteria.

The efficacy of nano finish was analyzed against antimicrobial activity of pathogenic microorganisms i.e. *P. aeruginosa*, *E. coli*, *S. aureus*, *B. cereus* and *Trichoderma* after 5, 10, 15 and 20 wash cycles. The microbial count of the washed fabric samples was compared with the finished unwashed (controlled) fabric samples. The results of efficacy of finished samples were recorded in terms of microbial resistance.

The results presented in Table 1 reveal that microbial count of cotton fabric finished with silver nanoparticles was 1.62×10^6 and 2.73×10^6 CFU/ml for *P. aeruginosa* and *E. coli*, respectively. The microbial count recorded for *S. aureus* and *B. cereus* was 1.41×10^6 and 1.72×10^6 CFU/ml, respectively. In case of unicellular fungi, *Trichoderma*, the microbial count was1.65×10^6 CFU/ml.

After 5 wash cycles microbial count of silver nanoparticles treated fabric was found to be 2.14×10^6 and 3.29×10^6 CFU/ml for *P. aeruginosa* and *E. coli*, respectively. The microbial count for *S. aureus* and *B. cereus* was recorded as $1.63\times10^6$and 2.17×10^6 CFU/ml, respectively. For unicellular fungi, *Trichoderma*, 1.96×10^6 CFU/ml microbial count was recorded.

Table 1: Antimicrobial activity of nano finished cotton fabric against growth of microorganisms

Wash cycles	Microbial count (CFU/ml)*				
	Gram negative bacteria		Gram positive bacteria		Unicellular fungi
	P. aeruginosa	*E. coli*	*S. aureus*	*B. cereus*	*Trichoderma*
AgNPs treated (Unwashed)	1.62×10^6	2.73×10^6	1.41×10^6	1.72×10^6	1.65×10^6
5	2.14×10^6	3.29×10^6	1.63×10^6	2.17×10^6	1.96×10^6
10	2.57×10^6	3.82×10^6	3.10×10^6	3.00×10^6	2.30×10^6
15	2.76×10^6	4.40×10^6	3.33×10^6	3.98×10^6	2.70×10^6
20	4.23×10^6	6.74×10^6	4.05×10^6	4.73×10^6	3.08×10^6

With increase in wash cycles from 5 to 20, the microbial count in terms of CFU/ml of silver nanoparticles treated fabric increased from 2.14×10^6 to 4.23×10^6 for *P. aeruginosa* and 3.29×10^6 to 6.74×10^6 for *E. coli*. For Gram positive bacteria, the microbial count increased from 1.63×10^6 to 4.05×10^6 CFU/ml for *S. aureus* and 2.17×10^6 to 4.73×10^6 CFU/ml for *B. cereus*. Increase in the microbial count of unicellular fungi *Trichoderma* was observed from 1.96×10^6 to 3.08×10^6 CFU/ml.

Table 2: Efficacy of nano finish against growth of microorganisms with respect to washing

Wash cycles	Percent reduction of microbial count (%)				
	Gram negative bacteria		Gram positive bacteria		Unicellular fungi
	P. aeruginosa	*E. coli*	*S. aureus*	*B. cereus*	*Trichoderma*
AgNPs treated (Unwashed)	98.21	97.49	98.23	98.34	96.15
5	97.63	96.97	97.95	97.90	95.41
10	97.15	96.48	96.10	97.10	94.63
15	96.95	95.95	95.82	96.15	93.70
20	95.32	93.80	94.91	95.43	92.80

The data in Table 2 highlight the percent reduction in the antimicrobial activity of silver nanoparticles treated cotton fabric samples with increased number of wash cycles. The reduction in growth of microbes on unwashed cotton fabric against *P. aeruginosa* and *E. coli* was observed to be 98.21 and 97.49 percent, respectively. After 5 wash cycles, the reduction in microbial growth on washed cotton fabric sample was 97.63 and 96.97 percent against Gram negative bacteria *P. aeruginosa* and *E. coli*, respectively. After 10 wash cycles, the reduction value reached to 97.15 and 96.48 percent whereas 96.95 and 95.95 percent, respectively reduction was observed after 15 wash cycles. After 20 wash cycles, the reduction in microbial growth on washed cotton fabric sample was 95.32 percent for *P. aeruginosa and* 93.80 percent for *E. coli*.

The microbial reduction in controlled cotton fabric sample was 98.23 and 98.34 percent against *S. aureus* and *B. cereus* (gram positive bacteria). The microbial growth reduction against *S. aureus* and *B. cereus* (gram positive bacteria) was found to be 97.95 and 97.90 percent after 5 wash cycles. The reduction value reached to 96.10 and 97.10 percent after 10 wash cycles and 95.82 and 96.15 percent, respectively after 15 wash cycles. After 20 wash cycles, the reduction in microbial growth on washed cotton fabric sample was 94.91 and 95.43 percent against *S. aureus* and *B. cereus* (gram positive bacteria).

The controlled cotton fabric sample showed a microbial reduction of 96.15 percent against *Trichoderma*. The reduction in microbial growth of unicellular fungi *Trichoderma* was found to be 95.41 percent in washed fabric sample after 5 wash cycles. It was found that the reduction value reached to 94.63 percent after 10 wash cycles, 93.70 percent after 15 wash cycles and 92.80 percent after 20 wash cycles.

It was revealed that the cotton fabric samples finished with silver nanoparticles synthesized from *neem* leaves extract resulted in good wash durability after 20 wash cycles. The findings concluded that though the antimicrobial efficacy of nano-finished fabric decreased with increase in wash cycles but the reduction in antimicrobial rate of all the tested microorganisms was still more than 92.00 percent even after 20 wash cycles.

Conclusion

The green-synthesized silver nanoparticles from *neem* leaves extract demonstrated remarkable antimicrobial efficacy across all the tested microorganisms. When applied as a nano finish, they significantly enhanced the antimicrobial properties of cotton fabric while maintaining its inherent comfort. Moreover, the treated fabric retained durable antimicrobial efficacy even after 20 wash cycles. Utilizing *neem* leaves for synthesizing silver nanoparticles proved to be a cost-effective, straight forward and eco-friendly method. This green approach to develop textile products with an antimicrobial herbal finish avoids the risks associated with harmful reducing or capping agents, highlighting its environmental sustainability and safety.

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