Malaysian Journal of Chemistry, 2026, Vol. 28(1), 236-244
(Special Issue: *3rd International Conference on Industry-Academia Initiatives in Biotechnology & Chemistry, iCIABC2025*)

Green-Synthesized Magnesium Oxide using Pomegranate Rind Extract for Antibacterial Fabric Coating

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This study presents a sustainable approach for imparting antibacterial and deodorizing properties to textile fabrics using magnesium oxide (MgO) synthesized via a green route. Pomegranate (*Punica granatum L.*) rind extract (PRE), rich in polyphenolic compounds, was employed as a reducing and stabilizing agent in the biosynthesis of MgO. The synthesized MgO were applied onto cotton, polyester, and blend wool fabrics using a dip-dry coating technique. Optimization experiments identified 4 g of rind powder extracted at 130 °C and a 10 mL extract volume as the most effective formulation. Antibacterial efficacy was assessed against *Brevibacterium linens*, *Cutibacterium acnes*, and *Staphylococcus epidermidis* using the disc diffusion method. All coated fabrics exhibited antimicrobial activity, with blend wool showing the most pronounced inhibition zones. Gas chromatography–mass spectrometry analysis confirmed the absence of volatile organic compounds typically associated with body odour in the coated samples. The study demonstrates that PRE-mediated MgO coatings offer a dual-function textile solution for antibacterial protection and odour suppression, using a green, cost-effective, and scalable method.

Keywords: Green synthesis, magnesium oxide nanoparticles, pomegranate rind extract, antibacterial, fabric coating

Received: July 2025; Accepted: November 2025

The advancement of nanotechnology has significantly transformed the textile industry by enabling the development of functional fabrics with enhanced properties such as antibacterial activity, breathability, and durability. Among these, antibacterial textiles have garnered increasing attention due to their potential to mitigate microbial growth on clothing surfaces, thereby reducing the risk of infections and controlling body odour. Historically utilized in healthcare settings for applications such as hospital linens and surgical garments, the demand for antibacterial fabrics has now expanded to include sportswear, home furnishings, and everyday apparel, driven by heightened public awareness of hygiene and health.

Metal oxide nanoparticles (NPs) have emerged as potent antimicrobial agents owing to their broad-spectrum activity, chemical stability, and non-toxic nature. In particular, magnesium oxide (MgO) nanoparticles are recognized by the U.S. Food and Drug Administration (FDA) as safe materials and have demonstrated effectiveness against both gram-positive and gram-negative bacterial strains [1, 2]. Their mechanism of action typically involves membrane disruption, oxidative stress induction, and the release of metal ions, all of which contribute to bacterial cell death.

While conventional synthesis methods of MgO NPs often involve hazardous chemicals and energy-intensive procedures, green synthesis provides an eco-friendly alternative by utilizing plant-based extracts as reducing and stabilizing agents [3]. Pomegranate (*Punica granatum L.*) rind extract (PRE) is a promising candidate for green synthesis due to its high content of polyphenols and flavonoids, which exhibit intrinsic antimicrobial properties [4,5]. These bioactive compounds not only facilitate nanoparticle formation but may also synergize with MgO to enhance antibacterial efficacy.

This study aims to synthesize MgO nanoparticles via a green route using PRE and apply them as antibacterial coatings on cotton, polyester, and blend wool fabrics. The antibacterial performance was evaluated against *Brevibacterium linens*, *Cutibacterium acnes*, and *Staphylococcus epidermidis*, common

†Paper presented at the 3rd International Conference on Industry-Academia Initiatives in Biotechnology & Chemistry

gram-positive bacteria implicated in human body odour [6]. Additionally, the study assessed the coated fabrics' ability to suppress volatile organic compound (VOC) emissions through gas chromatography–mass spectrometry (GC-MS) analysis. The findings contribute to the development of sustainable antimicrobial textiles with dual functionality: bacterial inhibition and odour control.

EXPERIMENTAL

Chemicals and Materials

Pomegranate (*Punica granatum L.*) rind powder was obtained from a local herbal supplier in Malaysia. Magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$) served as the metal precursor and was procured from Bendosen (Malaysia). Deionized water was used as the solvent throughout the study. Fabric substrates included cotton, polyester, and blend wool (comprising 20% wool, 33% Tencel, and 47% anti-pilling acrylic), acquired from a local textile distributor. All reagents used were of analytical grade and applied without further purification.

Preparation and Optimization of Pomegranate Rind Extract

PRE was prepared by dispersing 2 g, 4 g, and 8 g of rind powder in 100 mL of deionized water and heating at three different temperatures (30 °C, 80 °C, and 130 °C) under continuous stirring for 1 hour. The solutions were filtered through Whatman No. 1 filter paper and stored at 4 °C prior to use.

Green Synthesis of Magnesium Oxide Nanoparticles

MgO NPs were synthesized via a green synthesis route using PRE as both the reducing and stabilizing agent. One parameter of biosynthesis method was studied, namely volume of the polymer matrix (5, 10 and 15 mL). Other synthesis conditions were kept constant. The best compositions for each formulation were determined based on the highest antibacterial efficiency of coated fabrics towards three types of gram-positive bacteria. A fixed volume of optimized PRE was added dropwise to an aqueous solution of magnesium nitrate precursor under constant stirring at ambient temperature. The mixture was left to react until nanoparticle formation was visually indicated by a colour change and mild turbidity. The synthesized colloidal suspension was used immediately in the coating process.

Fabric Preparation and Coating Procedure

All fabric samples were pre-treated with ethanol to remove surface contaminants. The fabrics were immersed in 95% ethanol and subjected to ultrasonication at 35 °C for 15 minutes, then air-dried at room temperature for 8 hours. Coating was performed using a dip-dry method with the number of coatings (1×, 2× and 3×) wherein fabric specimens were immersed in the MgO nanoparticle solution for 15 minutes, followed by air-drying for 24 hours at ambient conditions (20–26 °C).

Antibacterial Activity Test

The antibacterial activity of coated and uncoated fabrics was evaluated using the disc diffusion method against *Brevibacterium linens (B. linens)*, *Cutibacterium acnes (C. acnes)*, and *Staphylococcus epidermidis (S. epidermidis)*. Bacterial suspensions (9.0×10^8 CFU/mL) were cultured on Tryptone Soya Yeast Extract (TSYE) agar for *B. linens*, Columbia Blood Agar Base (CBAB) with expired human blood for *C. acnes*, and Mueller Hinton (MH) agar for *S. epidermidis*. Circular discs (6 mm) of fabric samples were aseptically placed onto the inoculated agar plates alongside control antibiotic discs. Inhibition zones were measured after incubation (48–72 hours) to assess antibacterial efficacy.

Mechanical Properties of Fabric

Mechanical testing was carried out using a Universal Testing Machine (Tinius Olsen H25KS, USA). The tensile strength of coated and uncoated fabrics was determined in accordance with ISO 13934-1:2013 using the strip method. Tear strength was measured for cotton and polyester fabrics using ISO 13937-4:2000 (double tear test). All tests were performed under standardized atmospheric conditions (20 ± 2 °C, 65 ± 2% relative humidity) as specified in ISO 139:1937.

Air Permeability Test

The air permeability of coated and uncoated fabrics was evaluated using the SDL Atlas M021A Air Permeability Tester (USA), following ISO 9237:1995. Samples were conditioned at 20 ± 2 °C and 65 ± 2% relative humidity for 24 hours before testing.

Washing Durability

The washing durability of the nanoparticle coatings was assessed using ISO 6330:2012(E), which simulates domestic laundering. After repeated washing cycles, antibacterial performance was re-evaluated to determine coating retention and functionality.

Analysis of Volatile Organic Compounds

To determine the fabric's potential for odour control, VOCs were analysed via GC-MS using the Agilent 6890 Series GC System. The system utilized a BPX5 capillary column (30 mm × 0.25 mm, 0.25 μm film thickness) and helium as a carrier gas (flow rate: 1.2 mL/min). The injector was set at 250 °C and operated in spitless mode for 3 minutes. The oven temperature was programmed to hold at 40 °C for 3 minutes, then

ramp to 73 °C at 3 °C/min, and finally to 220 °C at 5 °C/min. The detection range was set to 40–450 Da using electron impact ionization at 70 eV. The GC-MS conditions were modified according to Xin et al. (2013) [7]. VOCs absorbed by artificial sweat and extracted from both coated and uncoated fabrics were identified and compared.

RESULTS AND DISCUSSION

Optimization of Pomegranate Rind Extract Parameters

The antibacterial efficacy of PRE was significantly influenced by the extraction conditions. Table 1 presents the antibacterial activity for extracts obtained using varying powder quantities (2 g, 4 g, and 8 g) and extraction temperatures (30 °C, 80 °C, and 130 °C). Remarkably, 4 g of PRE extracted at 130 °C produced consistent antibacterial activity against all three tested gram-positive bacteria (*B. linens*, *C. acnes*, and *S. epidermidis*), without the occurrence of microbial contamination observed in higher concentrations. Therefore, this condition was selected as the optimized formulation for nanoparticle synthesis. Elevated extraction temperatures enhance the release of bioactive compounds such as flavonoids and polyphenols by improving solubility and mass transfer rates [8]. These phytochemicals demonstrate inherent antibacterial characteristics and serve as essential reducing and stabilizing agents, transforming metal ions into metallic nanoparticles while inhibiting their aggregation during production [9]. Antibacterial screening indicated that extracts obtained using 4 g of powder at 130 °C exhibited the highest and most consistent antimicrobial activity across all tested gram-positive bacteria. These conditions were therefore selected for subsequent synthesis steps.

Effect of Coating Parameters on Antibacterial Activity

Further optimization focused on the volume of PRE used during the green synthesis process and the number of coating cycles applied to the fabrics. The experiments revealed that the 10 mL PRE condition exhibited a comparatively stronger antibacterial effect than 5 ml and 15 ml. The latter showed early signs of microbial contamination, likely due to an excess of organic compounds [10]. Meanwhile, the low amount of plant extract to precursors resulting in incomplete reduction and stabilization of metal precursors which lead to large and ununiform NPs and finally may affect the NPs performance [11]. Additionally, performing single coating cycle was found to be optimal, as multiple coatings did not result in enhanced antibacterial efficacy. The coating cycle influences the thickness and stability of the biosynthesized coating [12]. However, the number of coating cycles did not affect the antibacterial property of the biosynthesis derived antibacterial NPs [13,14]. Few studies reported that the biocidal agents or antibacterial compounds of NPs are mainly affecting the antibacterial property of the coated fabric, rather than by the coating cycle [15,16].

Table 1. The antibacterial activities of PRE.

Bacteria	Temperature (°C)	Amount of pomegranate rind powder (g)		
		2	4	8
B. linens	30	-	-	-
	80	-	-	-
	130	√	√	√
C. acnes	30	-	-	-
	80	-	-	-
	130	-	√	√
S. epidermidis	30	-	-	-
	80	-	-	-
	130	-	√	√

Table 2. The inhibition zone value (mm) of coated fabrics against *B. linens*, *C. acnes*, *S. epidermidis* and antibiotic.

Bacteria species	Inhibition zone (mm)			
	Cotton	**Polyester**	**Blend wool**	**Antibiotic (Control)**
B. linens	2 mm	3 mm	7 mm	10 mm (Vancomycin)
C. acnes	2 mm	3 mm	6 mm	12 mm (Gentamicin)
S. epidermidis	2 mm	2 mm	3 mm	17 mm (Ampicillin)

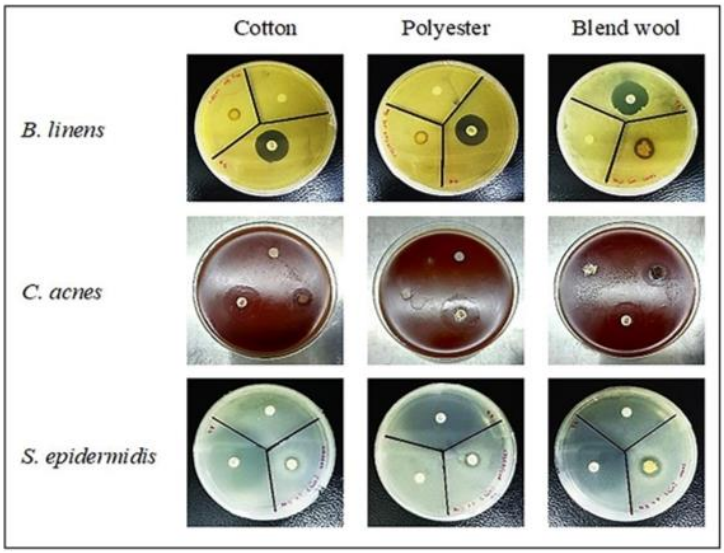

Figure 1. The antibacterial activities of the modified MgO particles coated fabrics against *B. linens*, *C. acnes* and *S. epidermidis*.

Antibacterial Activity of MgO-Coated Fabrics

The antibacterial performance of the green-synthesized MgO nanoparticle coatings was evaluated on cotton, polyester, and blend wool fabrics using the disc diffusion method. The quantitative inhibition zone diameters are presented in Table 2 and Figure 1.

All coated fabrics exhibited inhibitory activity against the bacterial strains, albeit lower than that of conventional antibiotics. Among the substrates, blend wool demonstrated the most pronounced activity, particularly against *B. linens*. This enhanced effect may be attributed to its higher thickness and fibrous structure, which promotes increased nanoparticle retention [15]. Conversely, the relatively lower inhibition observed on cotton may be due to the loss of potassium ions during the coating process, which potentially diminishes its antimicrobial interface [17]. The hydrophobicity of polyester is likely responsible for its moderate efficacy, limiting uniform nanoparticle deposition [18].

Mechanism of Antibacterial Activity of MgO Nanoparticles

The substantial antibacterial efficacy of magnesium oxide nanoparticles (MgO NPs) is attributable to a combination of various synergistic processes, notably involving the formation of Reactive Oxygen Species (ROS) and direct cell membrane rupture [19].

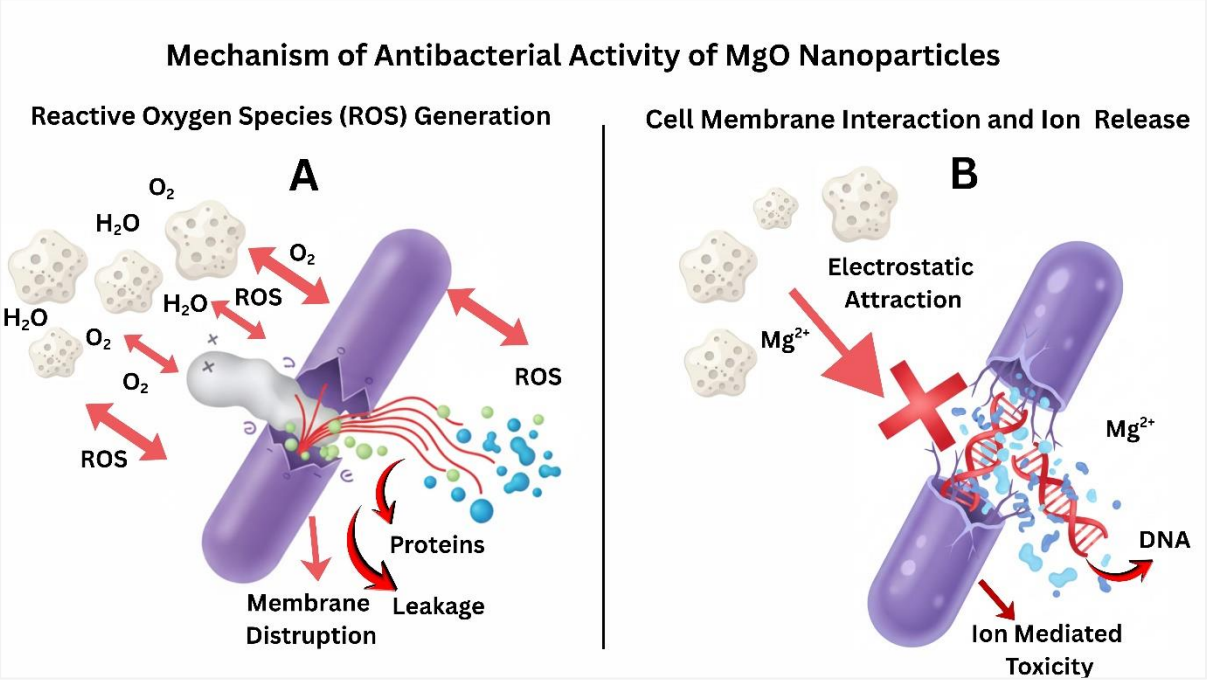

Figure 2. Illustration of Mechanism **of** Antibacterial Activity of MgO.

Reactive Oxygen Species (ROS) Generation:

When MgO NPs interact with the surrounding aqueous environment, they form extremely damaging ROS, such as superoxide anions (O_2^-), hydroxyl radicals (OH), and singlet oxygen ($^1O_2$) [20]. These species are produced on the active surface locations of the MgO NPs. The ROS permeate the bacterial cell wall and membrane, resulting to oxidative stress. This oxidative damage attacks key biological components including DNA, proteins, and lipids causing irreversible damage and ultimately leading to bacterial cell death (Figure 2 -A).

Direct Cell Membrane Interaction and Physical Damage:

MgO NPs possess a positive surface charge which facilitates a strong electrostatic attraction to the negatively charged surface of bacterial membranes (particularly effective against Gram-positive bacteria like *B. linens*, *C. acnes*, and *S. epidermidis*) [21]. This strong adhesion physically disrupts the cell membrane integrity. The sharp edges or corners of the nanoparticles can puncture or damage the membrane, leading to the leakage of essential intracellular contents and rapid depolarization, which compromises the cell's ability to regulate transport and homeostasis (Fig. 2 -B).

Release of Magnesium Ions (Mg^{2+})

While MgO is largely insoluble, a limited quantity of Mg^{2+} ions can be liberated, particularly in moderately acidic situations like the bacterial cell surface [22]. High local concentrations of these metal ions can interfere with the bacterial respiratory chain, disrupt enzyme activity, and hinder DNA replication, adding another layer to the overall biocidal effect (Figure 2 -B).

These combined effects membrane degradation giving entrance sites and ROS producing interior destruction are important to the substantial antibacterial effectiveness reported across the various coated materials (Table 3).

Mechanical Properties of Coated Fabrics

The mechanical integrity of the MgO-coated fabrics was assessed through tongue tear strength and breaking load measurements. Table 3 presents the results for coated and uncoated cotton, polyester, and blend wool fabrics. A marginal reduction in strength was observed for most fabric types following coating. Notably, coated blend wool exhibited a 7.63% increase in breaking load in the weft direction. This may be attributed to improved mechanical interlocking between nanoparticles and the fibre matrix. In contrast, polyester exhibited a decrease in both tongue tear strength and breaking load after coating, potentially due to degradation of the ester bonds under mildly acidic conditions introduced during extract-mediated synthesis [23]. Cotton fabric showed more pronounced strength reduction in the weft direction, likely due to its lower thread density in that orientation. This facilitated greater nanoparticle deposition, which may have stiffened the fibres and weakened structural resilience upon mechanical load.

Table 3 Tongue tear strength and breaking load of coated and uncoated fabrics.

Fabric	Tongue tear strength (N)		Breaking load (N)	
	Warp	Weft	Warp	Weft
Uncoated cotton	15.83 ± 1.852	15.58 ± 2.624	743 ± 9.626	355.1 ± 10.764
Coated cotton	16.67 ± 1.328	11.08 ± 0.471	720 ± 15.839	339.3 ± 12.221
Uncoated polyester	73.8 ± 3.982	100.8 ± 0.000	1268 ± 3.091	1685 ± 10.498
Coated polyester	60.8 ± 0.736	90.4 ± 0.849	1211 ± 14.522	1578 ± 16.573
Uncoated wool	-	-	366.7 ± 67.633	120.5 ± 3.001
Coated wool	-	-	258.1 ± 21.559	129.7 ± 3.456

Table 4 Fabric thickness and air permeability of coated and uncoated samples.

Fabric	Thickness (mm)		Air permeability (cfm)
	Warp	Weft	Warp
Uncoated cotton	0.26 ± 0.00	0.26 ± 0.00	40.4 ± 2.612
Coated cotton	0.26 ± 0.00	0.26 ± 0.00	37.9 ± 1.408
Uncoated polyester	0.35 ± 0.00	0.35 ± 0.00	20.8 ± 0.679
Coated polyester	0.35 ± 0.00	0.35 ± 0.00	20.4 ± 0.839
Uncoated wool	1.32 ± 0.00	1.30 ± 0.00	522.8 ± 9.520
Coated wool	1.26 ± 0.00	1.24 ± 0.00	507 ± 7.924

Air permeability is influenced by factors such as fabric density, yarn linear density, and fibre structure [24]. As shown in Table 4, a minor reduction in air permeability was observed in coated cotton (1.92%), likely due to pore blockage by deposited nanoparticles [25]. For polyester, no change in fabric thickness was recorded, attributed to the fabric's hydrophobic nature, which resists aqueous nanoparticle penetration. Interestingly, coated blend wool exhibited a reduction in thickness, suggesting fibre degradation during synthesis and increased porosity. This observation is consistent with studies reporting wool sensitivity to alkaline and acidic environments, which may weaken fibre integrity and enhance breathability [26].

To evaluate the wash durability of the MgO coatings, coated fabrics were subjected to up to five laundering cycles following ISO 6330:2012(E). The antibacterial activity was tested against *B. linens*, *C. acnes*, and *S. epidermidis* after each wash. A marked reduction in antibacterial activity was observed after the first wash cycle for all fabric types. These characteristics reduce surface contact and binding forces between the nanoparticles and fabric fibres [27]. Furthermore, the absence of additional binding agents or surface pre-functionalization likely contributed to coating instability during washing [28].

VOC Suppression Analysis by GC-MS

Fabric can develop unpleasant odours due to both internal and external factors related to the human body. Odour issues in fabrics arise from the presence of VOCs produced by bacterial metabolism of sweat compounds and fabric fibres. Secondary odours, which develop from either biotic or abiotic processes within the fabric, are often more intense than primary odours originating from the adjacent axilla [29]. To evaluate odour control functionality, VOC profiling was performed using GC-MS. Table 5 lists the major VOCs detected in uncoated fabrics and the absence of such compounds in MgO-coated samples. The complete absence of detectable VOCs in all coated fabric samples indicates that the MgO coatings synthesized with PRE effectively suppressed the bacterial metabolism responsible for body odour. These findings complement the antibacterial test results and support the application of the coating as a dual-function material for hygiene textiles.

Table 5. The volatile organic compounds detected in coated and uncoated fabrics.

Fabric	VOCs Detected (Uncoated)	VOCs Detected (Coated)
Cotton	Phosphoric acid Hexanoic acid Octanoic acid	None
Polyester	Ethyl carbamate	None
Coated wool	Acetic acid	None

CONCLUSION

The green synthesis of MgO NPs using PRE has been successfully demonstrated as an effective and environmentally friendly strategy for developing antibacterial textile coatings. The optimized extract formulation (4 g powder at 130 °C) yielded stable MgO nanoparticles capable of imparting antimicrobial functionality to cotton, polyester, and blend wool fabrics. Blend wool showed the highest antibacterial efficacy, while mechanical and air permeability tests indicated minimal impact on fabric integrity. However, the coatings lacked durability, with antibacterial performance lost after a single wash cycle. To circumvent this constraint, future studies should explore the introduction of biopolymeric crosslinkers such as chitosan, which may create hydrogen bonds and electrostatic interactions with both nanoparticles and fabric strands. This technique is projected to considerably boost adhesion strength and washing durability, while keeping the eco-friendly nature of the synthesis. GC-MS analysis confirmed that the coatings also suppressed the formation of volatile organic compounds, effectively reducing body odour potential. This study reinforces the promise of bio-based nanoparticles for hygiene-oriented textile applications and emphasizes the significance of developing more permanent and strongly adherent antibacterial coatings in future research.

ACKNOWLEDGEMENTS

The authors gratefully acknowledged the grant provided by Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) under RDU Grant (Vote number: RDU2203100).

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