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Plasma-treated bamboo wound dressing functionalized with green-synthesized silver nanoparticles

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The present study investigates the fabrication of a wound dressing using oxygen plasma-treated regenerated bamboo spunlace nonwoven fabric coated with green-synthesized silver nanoparticles (AgNPs) derived from *Tridax procumbens* leaf extract. The fabricated wound dressing exhibits enhanced physical properties, including increased mass per unit area, elongation, air permeability, water vapour permeability, and wickability. A slight reduction in thickness and breaking force is observed. The wound dressing exhibits significant antimicrobial activity against wound pathogens, supported by field emission scanning electron microscopy (FESEM) analysis, which reveals a higher distribution of AgNPs on the plasma-treated surface. Additionally, the fabricated wound dressing shows improved free swell absorptive capacity, making it suitable for the treatment of moderate to heavily exuding wounds. These findings highlight the potential of this novel wound dressing for advanced wound care applications.

Keywords: Antimicrobial activity, Bamboo spunlace nonwoven, Green synthesis, Silver nanoparticles, *Tridax procumbens*, Wound dressing

The application of textiles in medicine has a long tradition. Medical textiles has emerged as an important growing sector with great expansion in wound care products. The need for wound dressings that can combine traditional characteristics with modern functionalities for significantly improved therapeutic properties is constantly evolving. Unlike traditional dressings, advanced wound dressings are required to have biological activity either on their own or through the release of bioactive constituents. The incorporated antimicrobial components accelerate the wound healing process by acting as debriding agents for the removal of necrotic tissue and aid in tissue regeneration by preventing or treating infections at the wound site[1]. Due to high porosity and larger surface area, nonwoven fabrics are widely used as dressing materials[2]. Among the nonwovens, spunlace fabrics are predominant in medical textiles because of their comfort, safety, conformability, relatively good strength and high absorption qualities[3].

With the herbal renaissance worldwide, traditional medicinal herbs and their isolated active constituents are being explored for curing diseases. Traditional medicinal plants employed in folk medicines are found to be beneficial in wound care[4]. One such plant associated with therapeutic properties is *Tridax procumbens*, which belongs to the Daisy family and is well known for several pharmacological activities. It is extensively used in Indian traditional medicine for wound healing, and its leaf extract is used to check haemorrhage from cuts, bruises and wounds[5].

Nanotechnology offers tremendous possibilities for enhancing the process of wound treatments. Silver nanoparticles (AgNPs) are synthesized by several routes, among which plant-mediated green synthesis of AgNPs has become a progressing branch of nanotechnology[6]. Biosynthesis of nanoparticles using plant extracts is considered a valuable alternative to chemical methods since it is speedy, economical and eco-friendly[7].

Cellulosic materials and derivatives are often used as host materials in dressings for the treatment of pressure sores and burns. Bamboo, a natural cellulosic material that is soft, comfortable and eco-friendly, has a wide range of medical applications[8]. The most beneficial property of bamboo is its antibacterial activity[9]. Due to the hollow cross-section of bamboo fibres, bamboo fabrics possess high breathability, making them cool and comfortable to wear. Being hygroscopic, it absorbs three times its weight of water[10].

Due to ecological concerns, thermodynamic non-equilibrium gaseous plasma is a preferred and acceptable alternative to chemical processes for modifying the host cellulosic material to achieve superior hydrophilicity[11]. Plasma process parameters such as discharge power, exposure duration, gas flow rate, gas type and inter-electrode spacing play a pivotal role in determining the surface properties of treated fabric[12]. Oxygen plasma-treated polymeric

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surfaces result in improved hydrophilicity due to the presence of polar functional groups and rich surface morphology[13]. Improved hydrophilicity and antimicrobial activity are important requirements for wound dressing. This study investigates the fabrication of advanced wound dressings using oxygen plasma-treated bamboo spunlace nonwoven fabric coated with green-synthesized AgNPs derived from *T. procumbens*. The research evaluates the physical properties and antimicrobial activity of the modified fabric, with the goal of developing superior wound care solutions.

Experimental

Regenerated bamboo spunlace nonwoven fabric, purchased from the South Indian Textile Research Association (SITRA), Coimbatore, was used in this study. The fabric had a surface mass of 111.6 g/sq.m (ISO 9073-1) and a thickness of 0.6 mm (ASTM D 1777). The samples underwent plasma treatment following the protocol described by Manjula *et al.*[14]. The leaf extraction and biosynthesis of AgNPs were conducted as outlined in Manjula *et al.*[15]. The process flowchart for green synthesis of AgNPs from *T. procumbens* is shown in Fig. 1.

Control and plasma-treated fabric samples were coated with green-synthesized AgNPs using the exhaust method[16]. A solution containing 60 ml of 2 mM silver nitrate was reduced to AgNPs using 6 ml methanolic leaf extract of *T. procumbens*. The fabric samples were impregnated in the nanoparticle solution at 5% concentration based on the material's weight. The process was conducted overnight in an Erlenmeyer flask covered with aluminium foil under mild shaking conditions. The samples were then removed, air-dried at 25 ℃ and used for further evaluation.

Fabrication of Wound Dressing

The control and treated bamboo spunlace nonwoven fabric samples were used as absorbent pads for wound dressing fabrication. The control fabric (CNT) served as the untreated reference, while CNTNP represented the control fabric coated with nanoparticles, and PTNP denoted plasma-treated fabric coated with nanoparticles. Samples were cut into varied shapes, and a waterproof polyethylene film coated with medical-grade adhesive was attached to the absorbent pad, along with silicone release paper, as shown in Fig. 2.

Physical Properties

The physical properties of the control and treated samples were assessed using standard protocols. Ten samples were examined for each test, and average results were reported. The standard methods used are ISO 9073-1 for mass per unit area, ASTM D1777 for

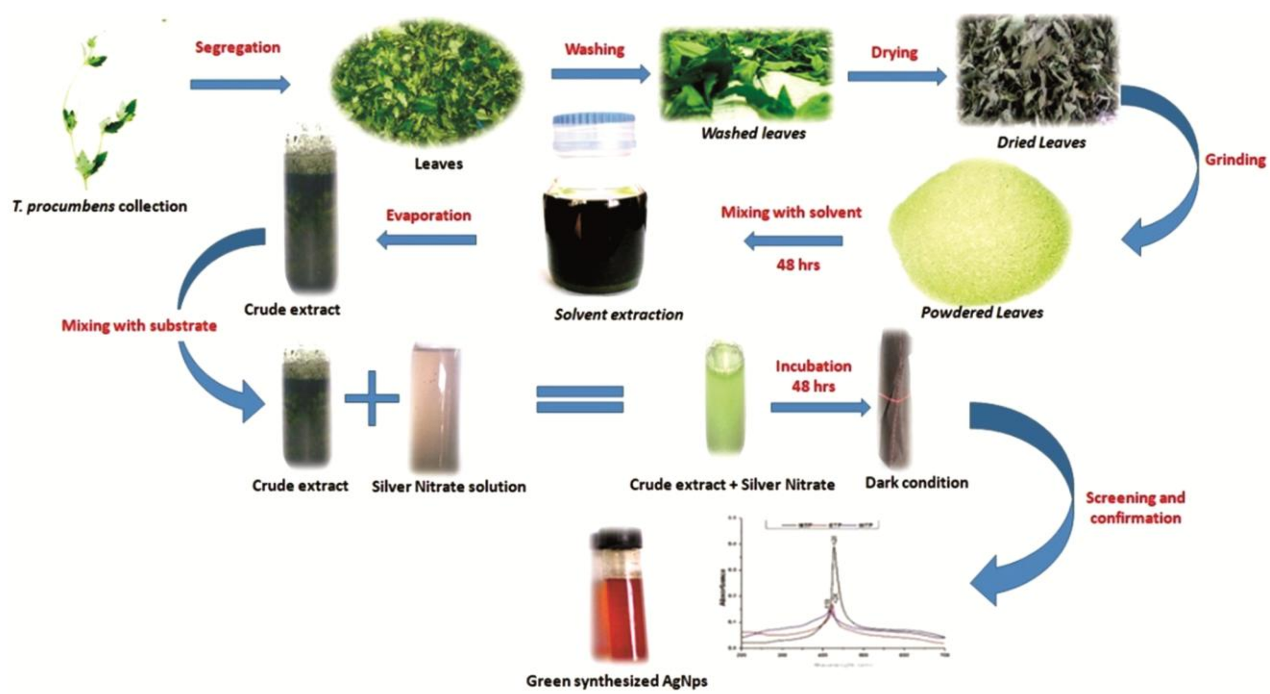

Fig. 1 — Green synthesis of AgNPs of *T. procumbens* leaves

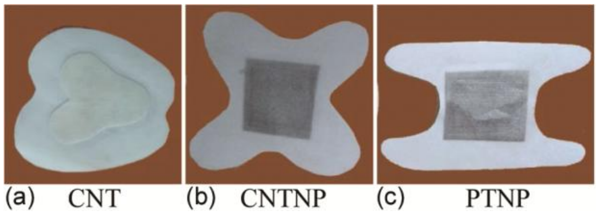

Fig. 2 — Wound dressings prepared from bamboo spunlace nonwoven fabric (a) control (b) control + nanocoated, and (c) plasma treated + nanocoated

thickness, ISO 9073-3:1989(E) for breaking force and elongation, ASTM D737 for air permeability, ASTM E96-95 Option 'B' test method for water vapour permeability, ISO 9073-6:2000(E) for vertical wicking test and EN 13726-1:2002(E)3.2 for free swell absorptive capacity.

Antibacterial Activity

Antibacterial activity was evaluated using the Mueller-Hinton agar plate method, wherein overnight-grown bacterial cultures were swabbed onto agar plates with sterile cotton swabs. A 1.0 cm^2 piece of coated fabric was placed at the centre of each agar plate and incubated for 24 h[17]. Zones of inhibition were measured using a millimetre ruler. Antibacterial activity was studied against *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Streptococcus pyogenes, Serratia marcescens* and *Bacillus subtilis*.

Field Emission Scanning Electron Microscope (FESEM) Analysis

The coated fabrics were analyzed using a Sigma HV – Carl Zeiss FESEM equipped with a Bruker Quantax 200 – Z10 EDS detector. The FESEM scans, performed in a zig-zag pattern, provided detailed visualization of the AgNP coating, with a thickness ranging from 1.5 to 3.0 nm.

Results and Discussion

Antibacterial Activity of Green Synthesized AgNPs

The antibacterial activity of AgNPs synthesized from the methanolic extract of *T. procumbens* leaves demonstrate significant inhibition of growth in six human pathogens, *S. aureus, E. coli, P. aeruginosa, S. pyogenes, S. marcescens* and *B. subtilis*(Table 1 and Fig. 3). The inhibition zones increase with higher concentrations of AgNPs. The zone of inhibition for *S. aureus, E. coli, P. aeruginosa, S. pyogenes, S. marcescens, B. subtilis* measures 21.5 mm, 20.0 mm, 21.0 mm, 16.0 mm, 21.0 mm, 18.0 mm and 21.6 mm, respectively.

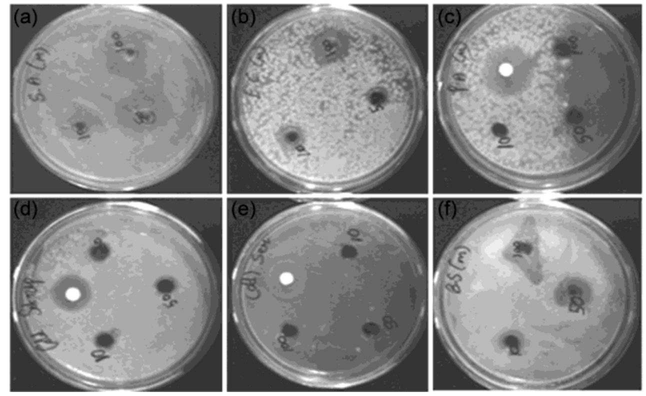

Fig. 3 — Antibacterial activity of AgNPs of *T. Procumbens* against (a) *S. aureus*, (b) *E. coli*, (c) *P. aeruginosa*, (d) *S. pyogenes*, (e) *S. marcescens* and (f) *B. Subtilis*

Table 1 — Antibacterial activity of AgNPs synthesized using methanolic extract of *T. procumbens*

Microorganism	Zone of inhibition, mm		
	10 μg/ml	50 μg/ml	100 μg/ml
Staphylococcus aureus	17.0	21.0	21.5
Escherichia coli	6.0	15.0	20.0
Pseudomonas aeruginosa	-	20.0	21.0
Streptococcus pyogenes	-	6.0	16.0
Serratia marcescens	12.0	18.0	18.0
Bacillus subtilis	15.0	21.0	21.6

Physical Properties

Physical properties of plasma-treated wound dressings, as reflected in Table 2, demonstrate that the mass per unit area increased for CNTNP and PTNP compared to CNT. Fabric weight increases due to penetration and coating of nanoparticles[18]. The PTNP sample shows a slightly higher mass, likely due to increased absorption and deposition of AgNPs on the etched surface of oxygen plasma-treated sample. Adhesion of textiles is improved due to etching, ablation, cleaning and activation of plasma-treated surface[19].

The PTNP sample exhibits a slight reduction in thickness (0.57 mm) compared to CNT (0.60 mm) and CNTNP (0.66 mm). Ablation and etching of plasma-treated surfaces due to the bombardment of high-energy ions and radicals may have caused a reduction in fabric thickness.

Breaking force results (Table 2) show that CNTNP exhibits the highest breaking force in both machine and cross directions.The PTNP sample shows a slight reduction, attributed to the etching phenomenon caused by plasma treatment. Even though plasma treatment has contributed to the reduction of breaking force compared to the control sample, the differences

Table 2 — Physical properties

Sample	Mass per unit area GSM	Thickness mm	Breaking Force, N		Elongation, %	
			Machine direction	Cross direction	Machine direction	Cross direction
CNT	111	0.60	198	151	37	26
CNTNP	116	0.66	220	172	32	21
PTNP	119	0.57	189	134	40	30

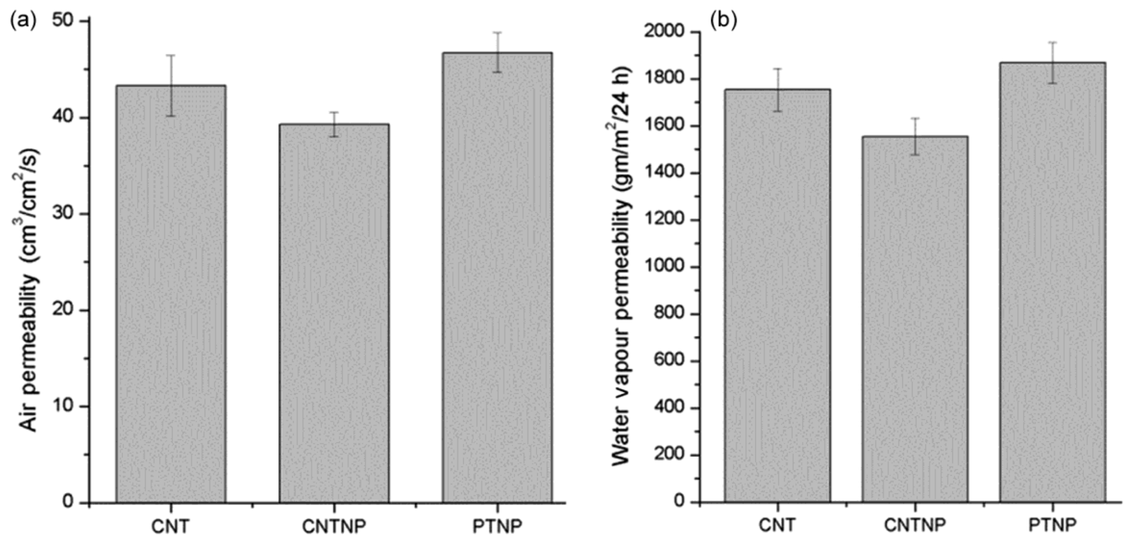

Fig. 4 — (a) Air permeability and (b) water vapour permeability

are not as pronounced. Elongation at break shows an inverse relationship with breaking force. CNTNP displays a reduction in elongation at break in contrast to PTNP, which exhibits a higher value. This increase in PTNP is attributed to plasma treatment, which resulted in an etched surface accounting for improved elasticity of the fabric. Though plasma treatment results in a slight reduction of breaking force, its impact is likely negligible. The tensile properties of fabrics determined as breaking force and elongation are particularly important in developing wound dressings as they should not tear during placement and removal, causing patient discomfort. Moreover, it has to be pliable, aiding in easy handling during frequent changes of dressings.

PTNP sample outperforms others in air permeability [Fig. 4 (a)]. It indicates that the plasma treatment significantly impacts the air permeability of fabrics. The surface roughness caused by plasma etching might have enlarged the void between fibres, causing the sample to permeate more air[20]. Air permeability is an essential property of wound dressing as it influences the wound's breathing, affecting the wound healing rate.

PTNP also demonstrates higher water vapour permeability [Fig. 4 (b)]. It may be due to the adhesion of more number of AgNPs anchored, especially onto the cracks and grooves of etched surfaces, thereby paving the way for water vapour transfer through the voids and spaces between the fibres. Water vapour permeability is another crucial characteristic requirement of a wound dressing as it measures the amount of water vapour lost from the wound bed over a period of time. Water vapour permeability must neither be too high nor too low as in either of the cases, the former may result in excessive dehydration in the wound area, and the latter may cause deceleration of wound healing.

Figure 5 (a) shows that PTNP exhibits the maximum wicking height in both machine and cross directions. It is shown that wicking height has significantly improved due to plasma treatment despite increased adhesion of AgNPs on the etched plasma-treated surface. It might be explained by the fact that the creation of polar functional groups on reactive oxygen plasma particles increases the surface energy of the fibrous assembly, which in turn amplifies the capillary action of nanoscale channels[21]. The increased contact area between the water and the fabric surface caused by the rougher etched surfaces with more grooves and cracks results in a faster water absorption[22]. Furthermore, a nonwoven surface with a

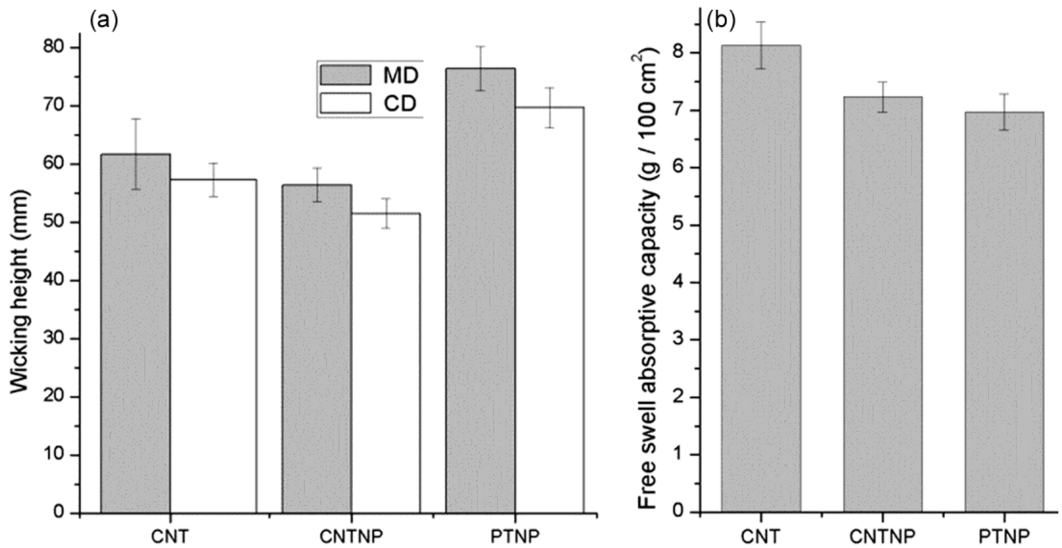

Fig. 5 — (a) Wicking height and (b) Free swell absorptive capacity

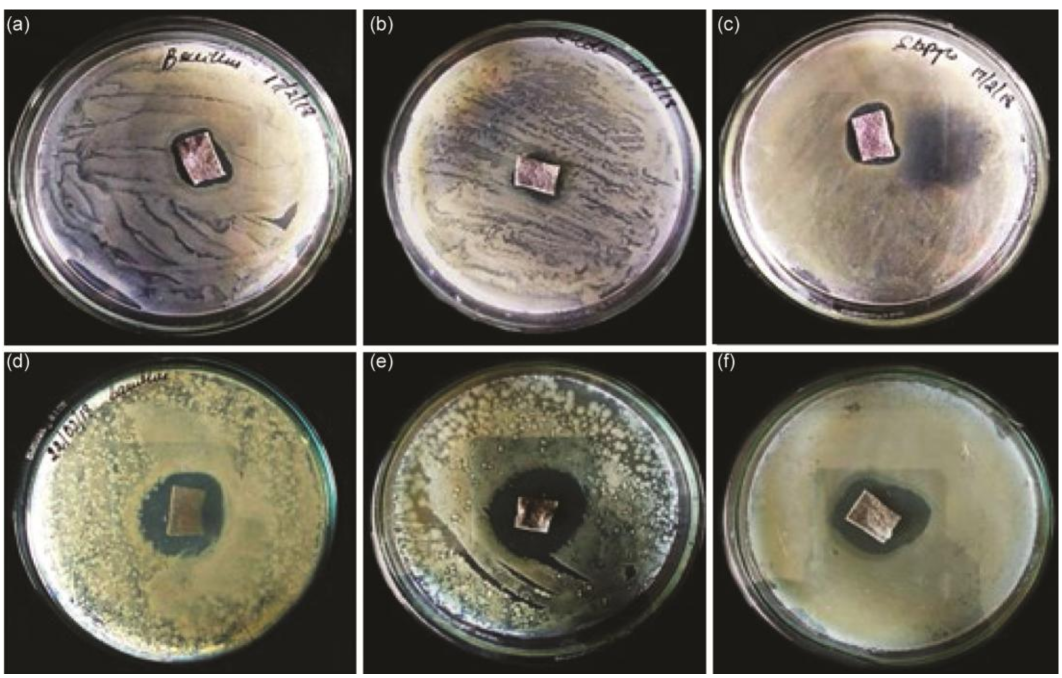

Fig. 6 — Antibacterial activity of CNTNP against (a) *B. subtilis,* (b) *E. coli,* (c) *S. aureus,* and PTNP against (d) *B. subtilis,* (e) *E. coli,* and (f) *S. Aureus*

highly porous structure would have facilitated improved plasma species penetration and accelerated capillary forces.

As shown in Fig. 5 (b), PTNP has a slightly reduced free swell absorbency compared to CNTNP and CNT. Plasma treatment might have influenced the pore size and geometry, impacting the deposition of AgNPs on the etched porous fibre assembly and affecting the mass of liquid retained in the pores. However, the fabricated dressing prepared using sample PTNP with a free swell absorptive capacity of 6.97g/100 cm^2 is well suited for the treatment of moderate to heavily exuding wounds.

Antibacterial Activity

The antibacterial activity results (Table 3 and Fig. 6) confirm the superior activity of PTNP against *B. subtilis* (22.3±0.06 mm), *E. coli* (26.7±0.03 mm), and *S. aureus* (19.7±0.06 mm) compared to CNTNP, likely due to higher nanoparticle adhesion on plasma-

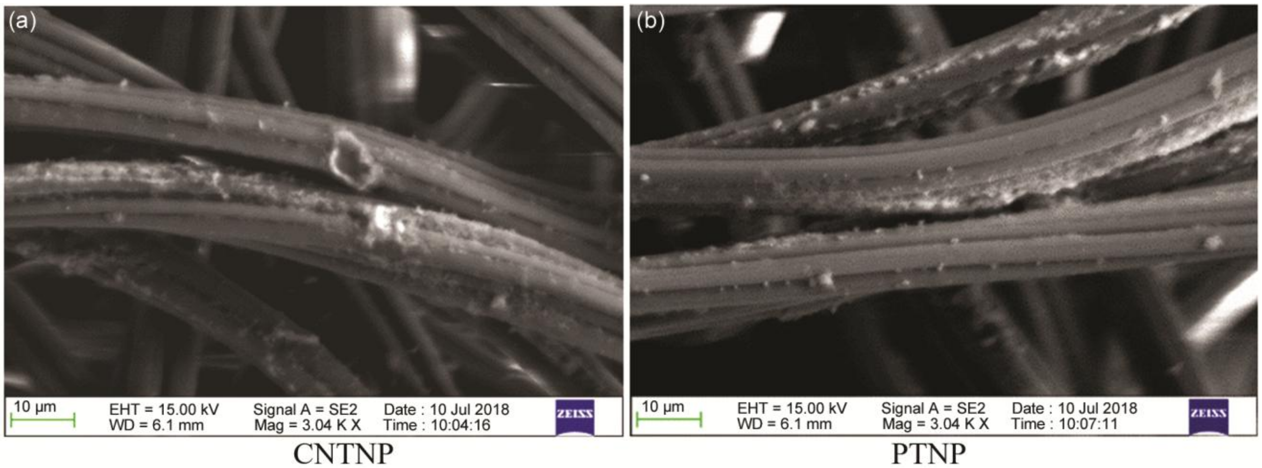

Fig. 7 — FESEM images of bamboo spunlace nonwoven fabric; (a) non plasma treated - coated with AgNPs (b) plasma treated -coated with AgNPs

Table 3 — Antibacterial activity of fabrics

Sample	Zone of inhibition, mm		
	B. subtilis	*E. coli*	*S. aureus*
CNTNP	1.4±0.06	1.2±0.06	1.53±0.03
PTNP	22.3±0.06	26.7±0.03	19.7±0.06

treated surfaces. Plasma-treated textile materials exhibit improved adhesion of AgNPs on fibre surfaces, enhancing the antimicrobial property of substrate[23].

FESEM Analysis

The fabrics' surface is observed at a magnification of 3.04 kx, and results reveal the presence of spherical shape AgNPs (<100 nm) (Fig. 7). PTNP shows the presence of deposition of more uniform and abundant nanoparticle deposition compared to CNTNP. This is due to the enhanced adhesion of nanoparticles onto the cracks and grooves of the etched fibres of plasma-treated fabric. Plasma-treated surface with rich morphology assists in adhering and bonding more AgNPs.

The study demonstrates that plasma-treated bamboo spunlace nonwoven fabric coated with green-synthesized silver nanoparticles (*T. procumbens*-AgNPs) exhibits enhanced functional properties, making it a promising material for wound dressing applications. The fabric showed a marginal decrease in thickness and breaking force but an increase in mass per unit area. Following plasma treatment, the material's elongation at break improved, enhancing its pliability. Improved patient comfort during wound healing has been linked to increased air permeability, water vapour permeability, and wickability of plasma-treated nanocoated cloth. FESEM analysis revealed the presence of a distribution of significantly AgNPs on plasma-treated fabric. The fabric demonstrated exceptional antibacterial efficacy against *S. aureus*, *E. coli*, and *B. subtilis*. The fabric showed enhanced free swell absorptive capacity, which enables it to treat moderate to heavily exuding wounds. The findings suggest that plasma treatment and green nanotechnology can synergistically enhance the performance of textile substrates, offering a sustainable and effective solution for advanced wound dressings.

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