

Fabrication of *T. Procumbens* Fiber for Diabetic Shoe Insole Functionalised with Nano Encapsulation for Antimicrobial and Wound-Healing Application

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ABSTRACT

Diabetes mellitus has become a major metabolic health concern worldwide. In chronic wounds, delayed proliferative phase initiation, decreased angiogenesis, compromised ECM production, and a protracted inflammatory response are all characteristics. One of the biggest problems facing the global healthcare system is chronic wounds, which are expensive to treat. Therefore, researching novel strategies to speed up wound healing is crucial. Natural fibre enhanced with nano-encapsulated antimicrobial agents acts as a potential agent for improving wound healing. These natural substances are readily available, simple to use, and very effective at managing wounds. This study aims to investigate natural fibre functionalized with nano-encapsulated antimicrobial agents to develop Diabetic shoe Insole fabrics with wound-healing performance. *T. procumbens* stem fiber is used in the current study. Untreated *T. Procumbens* fabric and the fabric finished with nano-encapsulation using *T. procumbens* leaf powder and Bitter gourd seed powder were comparatively assessed to define the impact of nano-encapsulation finishing treatment on the functional and biological characteristics of the textile substrates. The antimicrobial studies revealed that the developed textile systems had inhibitory activity against Gram-positive *S. aureus* and Gram-negative *E. coli*, demonstrating their potential broad-spectrum antibacterial activity. In addition, the fabrics offered antifungal activity against *A. niger*, indicating that the bio-finishing technology offered protection against microorganisms of both bacterial and fungal species. The observed antimicrobial response is particularly crucial for textile applications where microbial contamination, odor formation and hygienic performance come into consideration.

Keywords: Fabrication, Natural Fiber, Nano Encapsulation, Wound Healing, Diabetic melitus

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1. INTRODUCTION

The push for more sustainable and environmentally conscious innovations has popularized the use of natural fibers in textiles. Natural fibers are a promising alternative for synthetic fibers because of their abundant availability, low cost, and excellent biocompatibility. These characteristics make natural fibers suitable for the construction of medical textiles and hygiene products. (Subbiah G et al., 2025; Majeed et al., 2024; Karuppuchamy et al., 2024)

Among the many textile structures that exist, nonwovens are one of the fastest-developing structures. This is due to their versatility and easy and cost-effective fabrication. Conventional textile fabrics require a lengthy yarn formation process. Nonwovens utilize fibers that are bonded to one another using mechanical, thermal, or chemical methods. Then, these bonded webs can be formed rapidly and continuously (Hinchliffe et al., 2023; Periyasamy et al., 2026; Atalie et al., 2025). According to the International Nonwovens and Disposables Association (INDA), nonwovens are thermal, mechanically, or

chemically bonded fiber webs. Nonwovens have excellent breathability and absorbency, and a soft, lightweight structure.

Because of this, they are used widely in hygiene and medical products, as well as filtration and protective textiles (Puttegowda M et al., 2025; Sun, L., et al., 2025; Tubcil, M. S., et al., 2025; Šajn Gorjanc et al., 2024).

Natural plant fibers are environmentally friendly and have good mechanical properties. These characteristics have popularized the use of fibers from kenaf, hemp, flax, jute, and coir in textile and biomedical composites (Palanisamy, 2024; Nagaraja, 2024). Commercially used natural fibers can be restricted by geography. New sources are required to discover plant fibers which can be used in advanced textiles. These fibers need to have appropriate physical, chemical, and mechanical properties (Hindi et al., 2024; Assefa et al., 2024; Bhunia et al., 2023; Sheeba et al., 2023).

Diabetic foot complications are a significant global health issue. These complications can be attributed to impaired wound healing and an increased risk of foot infections.

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(Chen et al., 2024). The repair of a wound is slow in diabetic patients because of the chronic state of oxidative stress, impaired blood supply, reduced multiplication of cells, and overproduction of reactive oxygen species. (Maity et al., 2024). This situation leads to persistent inflammation and delays in developing new tissues. This has brought about the need for new multifunctional advanced textiles that can provide adequate cushioning, manage moisture, provide antimicrobial protection, and aid in wound healing (Gu et al., 2025; Lazar et al., 2024).

Because of their antimicrobial properties, low toxicity and environmentally safe profiles, herbal bioactive compounds can be used in advanced textiles and are a great replacement for synthetic antimicrobial agents, which can be harmful. *T. procumbens* leaf and Bitter gurad seed are excellent herbal source to be used in the field of functional medical textiles, given in wide range of properties. Herbal plant extracts are often used in “medical textiles. (Fernando et al., 2024; Reta et al., 2024; Sharma D et al., 2024; Mistry H et al., 2020; Lei, 2024).

Nanoencapsulation is a promising technique to enhance the sustained release of herbal bioactive compounds by providing a nanosized carrier that protects the herbal bioactive compound from degradation. In nanoencapsulation, the active ingredient (core) is completely surrounded by a coating that can be a shell or a matrix. Diffusion or external stimuli such as pH changes, enzymes, or mechanical stress can induce the release of the encapsulated ingredient. The controlled release system improves the stability, persistence, and therapeutic efficacy of the herbal finishes used in the textile substrates (Chowdhury et al., 2024; Sultan M et al., 2024; Han et al., 2024).

While the numerous reports have dealt with the use of natural fiber-based nonwoven materials and the use of herbal functional finishes separately, little to no literature exists that integrates *T. procumbens* fiber based nonwoven fabric with nano encapsulated *T. procumbens* leaf powder and Bitter guard seed powder, particularly in the context of diabetic footwear. Additionally, the study of the functional performance of the developed nonwoven in relation” to the morphology and/or structure of the material is largely unexplored. In light of these gaps, this study attempts to show the viability of using *T. procumbens* fibre for the fabrication of a sustainable nonwoven structure for a diabetic shoe insole, and subsequently functionalizing the insole with nano-encapsulated *T. procumbens* leaf powder and Bitter gourd seed powder to provide the insole with antimicrobial properties. A series of thorough characterization techniques (FTIR, SEM, XRD, and TGA) was performed on the nonwoven structure before and after the functional finish. The efficacy of the herb nano-encapsulated finish was assessed via a functional study based on antimicrobial and cytocompatibility properties for diabetic foot care. The results showcase the integration of sustainable natural fibers and the fiber reinforced composite technology for the design and production of

multifunctional diabetic shoe insole using eco-friendly and safe technologies.

2. MATERIALS AND METHODS

Materials Selection

Fresh stems and leaves of *T. procumbens* were collected from agricultural land in Periyanaickenpalayam, Coimbatore, Tamil Nadu, India. Cotton, Kapok and Low melting polyester fibers were purchased from the local market Coimbatore. Bitter guard seeds are procured from agriculture seed shop. Bio pectinase K was used to soften the extracted fibres. Citric acid has been utilized as a cross-linking agent in textile finishing, and bovine serum albumin (BSA) served as the wall material for nanoencapsulation. Potassium bromide (KBr) and other chemicals of analytical grade were purchased from GEM Scientific, Coimbatore.

Biological Retting

Stagnant water retting method was used to extract the natural fibers from the stems of *T. procumbens* plant. 10 kg of freshly cut stems were cleaned with water, and they were bundled and immersed in clean drinking water for 15 days in a concrete tank under regular ambient conditions. After 15 days *T. procumbens* stems were washed with clean water, then the reed stalks are combed to separate the fibers from the stems. After that *T. procumbens* separated fibers were shade dried for 7 days until no moisture remained. The dried and conditioned *T. procumbens* fibres are stored in ambient conditions for further processing as per the protocol of (Rao HJ et al, 2023) with small modifications.

Enzymatic Softening of Fibers

The presence of plant components such as cellulose, hemicellulose, pectin, and lignin led to the selection of Bio pectinase K as the preferred enzyme. Fiber weight was used to determine the treatment duration and enzyme concentration. Softening of the *T. procumbens* fibres was done using Bio Pectinase K enzyme to increase flexibility. Enzymatic softening was carried out in an aqueous medium at pH 4.5 with a material-to-liquid ratio of 1:40. The 5% (owf) enzyme concentration was added to the medium. The process temperature was maintained at 45°C for 5h. Following the enzymatic treatment, the fibers have been washed and dried in the shade. Softened fibers were conditioned and ready for the fabrication of nonwoven material as per the procedure of (G. Malarvizhi et al., 2017), with small modifications.

Fabrication of Nonwoven Shoe Insole

The thermal bonding method of fabric formation is found to be suitable for diabetic shoe insoles. In thermal bonding, all of the fibers are softened and fused together using heat and pressure, which also serves as an adhesive and keeps the temperature below melting. 60% of enzyme-treated *T. procumbens* fibers were cut to short staple lengths and blended with 30% cotton fiber, 5% kapok fiber, and 5% low-melting polyester fiber are blended for nonwoven fabric formation as per the protocol of (Kumari B et al., 2025) with small modifications. Blended fibers

were processed on a pre-opening machine for fiber homogeneity. Opened fibers were transferred to a carding machine for individualization for web formation. The fibrous web was consolidated into a mechanically stable nonwoven structure through the thermal bonding of the low-melting polyester fibres as per the protocol of (Venkataraman et al., 2023), with small modifications.

Nanoencapsulation of Herbal Extract

Collected *T. procumbens* leaf and Bitter guard seeds were dried in a room temperature as they cannot “be stored without drying to avoid breakdown of important compounds and contamination by microorganism. Grinding of the leaves and seeds was carried out using a mixer. The fine Powder is stored in an airtight container. The process of nanoencapsulation is done using *T. procumbens* leaf powder, and Bitter gourd seed powder is used as the core material with bovine serum albumin as the wall material. Bovine serum albumin and herbal extract were mixed with the help of a magnetic stirrer. A homogeneous emulsion was produced. In the optimized conditions of the encapsulation process, stable nano sized capsules with the potential of sustained release of the encapsulated bioactive material were produced. The nano-encapsulated formulation was kept at 4°C till the application of finishing as per the protocol of (Sumithra et al., 2012) with small modification.

Application of Nano-encapsulated Antimicrobial Finishing

Nano-encapsulated antimicrobial finishing was applied to the prepared *T. procumbens* nonwoven fabric using the pad-dry-cure method. The *T. procumbens* nonwoven fabrics were treated using the nano-encapsulated *T. procumbens* leaf powder and Bitter gourd seed powder suspension, which contained 8% citric acid, acting as a crosslinking agent, at a material-to-liquor ratio of 1: 20. Treatment has been carried out at 55°C for 30min. After” treatment, fabrics were cured under ideal conditions to increase finish durability. Nonwoven fabrics were conditioned for 24 h prior to characterization and biological assessment as per the protocol of (Jalali E et al., 2024) with small modification.

Characterization of *T. procumbens* and *Aloe vera* Fibre

FTIR analysis

FTIR analysis was performed on untreated and treated *T. procumbens* nonwoven Fabric to assess the chemical and functional groups. Analysis was performed on samples prepared by mixing and compressing the KBr discs. Every sample underwent a scan. with 32 repetitions, and the resultant spectra were analyzed within the range of 4000–400cm⁻¹ with a spectral resolution of 2cm⁻¹. (Vinod et al., 2020)

FESEM analysis

The morphological characterization of untreated and treated *T. procumbens* nonwoven Fabric was performed with a scanning electron microscope. Before being observed, the samples were sputter-coated with a thin layer of gold to improve their conductivity. Images were

recorded with varying magnification to evaluate the characteristics of the fibers and the uniformity of the coating. (Manimekalai et al., 2022)

XRD analysis

The phase nature of the materials was assessed with a Bruker D8 Advance X-ray diffractometer with a Cu K α X-ray tube ($\lambda = 1.5406 \text{ \AA}$). Diffraction patterns were assessed within the range of 2θ from 10 to 80° with a scan rate of 4° min⁻¹. The untreated and treated *T. procumbens* nonwoven fabric samples were assessed and compared for their phase nature. (Raja, 2022)

TGA analysis

The thermal degradation behavior and stability of the untreated and treated *T. procumbens* nonwoven fabrics were studied using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) (NETZSCH STA 449 F3). TGA samples of 5–10 mg were heated from 30 to 500°C with a 10 °C min⁻¹ heating rate and a 50mL min⁻¹ nitrogen purge. The thermal degradation and phase alteration of the untreated and treated *T. procumbens* nonwoven fabric samples were evaluated. (Feleke, 2023)

Biological Evaluation

Antimicrobial Test

Antibacterial activity of the untreated and treated *T. procumbens* nonwoven fabrics was performed. Mueller-Hinton agar plates were prepared. Pathogens, *Staphylococcus* and *E. coli*, were swabbed onto the prepared plates. Then the 5mm of treated and untreated samples were placed on the plates. Plates were incubated at 37 °C for 12hrs. The zone of inhibition was measured following incubation. Gentamicin was used as a positive control. Antifungal activity against *Aspergillus niger* was assessed using the agar diffusion method. The *Aspergillus niger* fungus was swabbed on potato dextrose agar. The treated and untreated *Aspergillus niger* samples were added and incubated at 28 °C for 72h. The antifungal reference standard was used to measure and compare the zone of inhibition. Amphotericin B was used as the reference (Deepa et al., 2024).

Cytotoxicity test

The cytotoxicity “of the untreated and treated *T. procumbens* nonwoven fabric was quantitatively assessed using the MTT assay to comply with in vitro standards. The L929 mouse fibroblast cell line was used for analysis. Dulbecco's Modified Eagle Medium was used to sustain the cell line with 10% FBS (v/v). Cells were plated into 96-well culture plates (2.5 × 10⁴ cells cm⁻²) and incubated for 24 h prior to exposure to the test samples. The effects on cell viability were assessed after 3, 12, and 24 h of exposure to the herbal extract in the diluted solution. A serum-free medium containing MTT was used in place of the culture medium (0.5mg mL⁻¹) and incubated for 4 h. The resultant formazan has been dissolved in DMSO, and the absorbance was recorded at 570 nm with 690 nm as a reference using the plate reader. The remaining cells were compared to the control, and the developed functional

finish was evaluated for cytocompatibility based on the viable cell percentage as per the protocol of (Manjula, 2019).

RESULTS AND DISCUSSION

FTIR analysis

Fourier Transform Infrared (FTIR) spectroscopy was used to analyse the interactions of the "*T. procumbens* nonwoven" fabric and nano-encapsulated herbal formulations prior to and after functional finishing. The untreated and treated *T. procumbens* nonwoven fabric spectral analyses are displayed in Fig.1, 1a and 1b. Untreated fabrics possess absorption bands typical of natural cellulose-based fibres, with a broad region of hydroxyl stretching within the range of 3200 to 3500 cm^{-1} , presence of aliphatic C-H within the range of 2900 cm^{-1} , and distinctive absorption bands within the fingerprint region of 1200 to 900 cm^{-1} , confirming the presence of cellulose and other lignocellulosic components. Following the nanoencapsulation of *T. procumbens* leaf extract and Bitter gourd seed powder, the *T. procumbens* fabric showed distinctive spectral changes. The hydroxyl region of the spectra was wider with a diminishing intensity, indicating that cellulose and the phenolic elements of the herbal formulation were engaged in stronger intermolecular hydrogen bonding. Changes in the carbonyl regions and increased intensity of the fingerprint region of the carbohydrates were seen, indicating the successful penetration of phytochemicals, primarily flavonoids, polyphenols, tannins and polysaccharides, onto the fiber surface. The finishing process did not affect the cellulose

absorption bands, indicating that the nanoencapsulation did not disrupt the cellulose framework and only impacted the fiber surface. *T. procumbens* nonwoven fabric showed comparable spectral behaviour. This shows that the finishing treatment is independent of fiber source. Instead, it shows effective immobilization of the herbal bioactive compounds. In addition, the absence of any undesirable absorption bands suggests good chemical compatibility of natural fibers with the encapsulated herbal coating. Hydrogen bonding and Physical adsorption are the main mechanisms of the interaction of the cellulose matrix with Nano-encapsulated Phytochemicals. The results of FTIR confirmed successful surface functionalization of nonwoven fabrics. The introduction of a hydroxyl- and phenol-rich active compound would be expected to improve the biologically related performance of the material through a sustained release of antimicrobial activity, while protecting the integrity of natural fibre.

Hameed et al. (2021) formulated a nanofiber consisting of Clove Essential Oil (CEO) encapsulated in chitosan and polyethylene oxide (PEO) polymer for enhanced wound healing and antimicrobial activity. The FTIR characterization of chitosan, PFE, CEO, and CEO loaded nanofiber shows the successful incorporation of clove essential oil into the nanofiber by the CEO NF spectrum at 2904 cm^{-1} and 1538 cm^{-1} . The CS spectra show a broad peak at 3248 cm^{-1} , which corresponds to the stretching of NH_2 and -OH. The peak at 1648 cm^{-1} is due to the deformation vibration of the C- O group in primary amines.

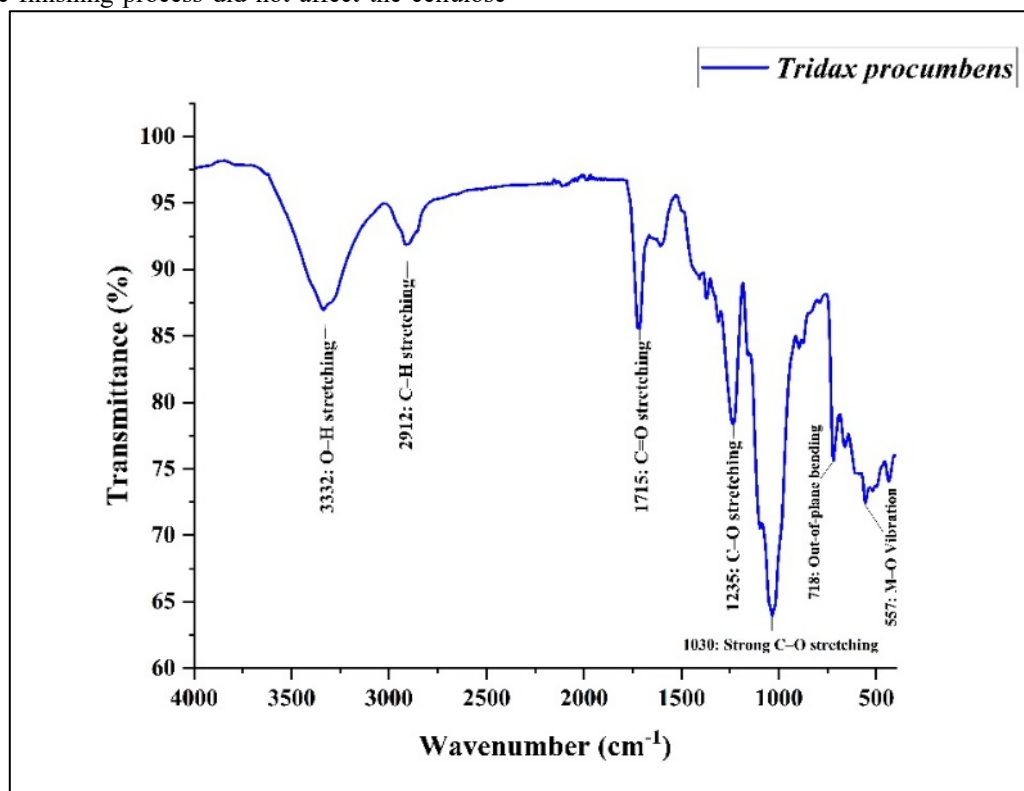


Fig. 1. FTIR analysis of untreated *T. procumbens* Non-woven Fabric

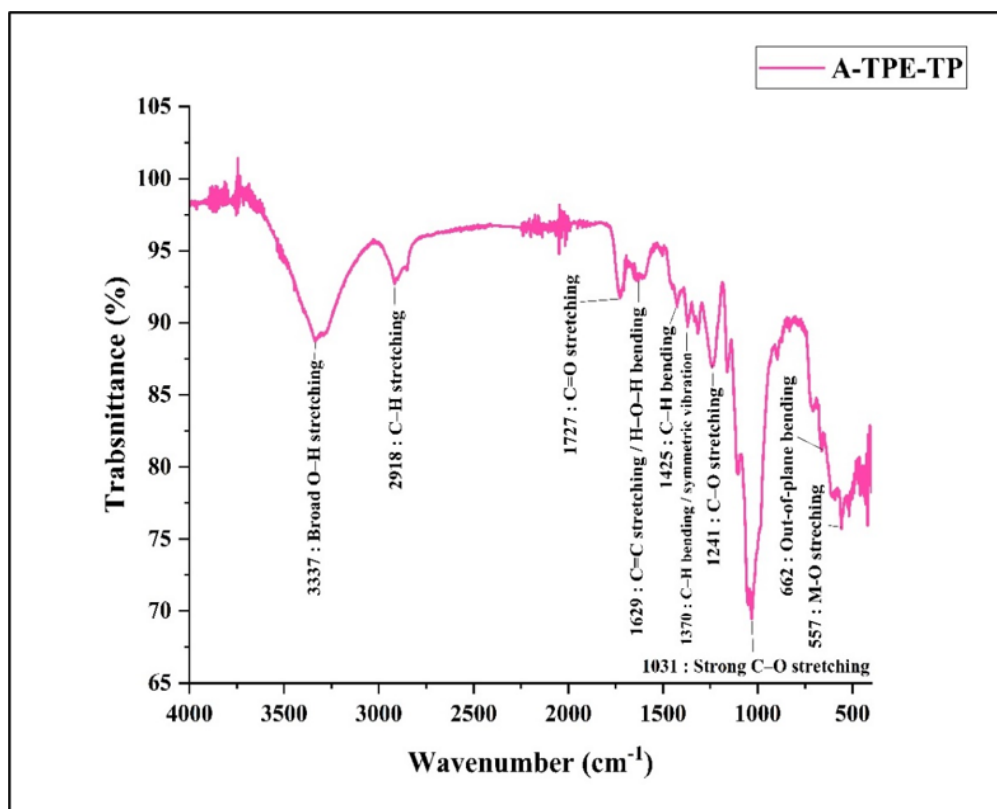


Fig 1 a. FTIR analysis of *T. procumbens* Non-woven Fabric treated with *T. procumbens* leaf powder

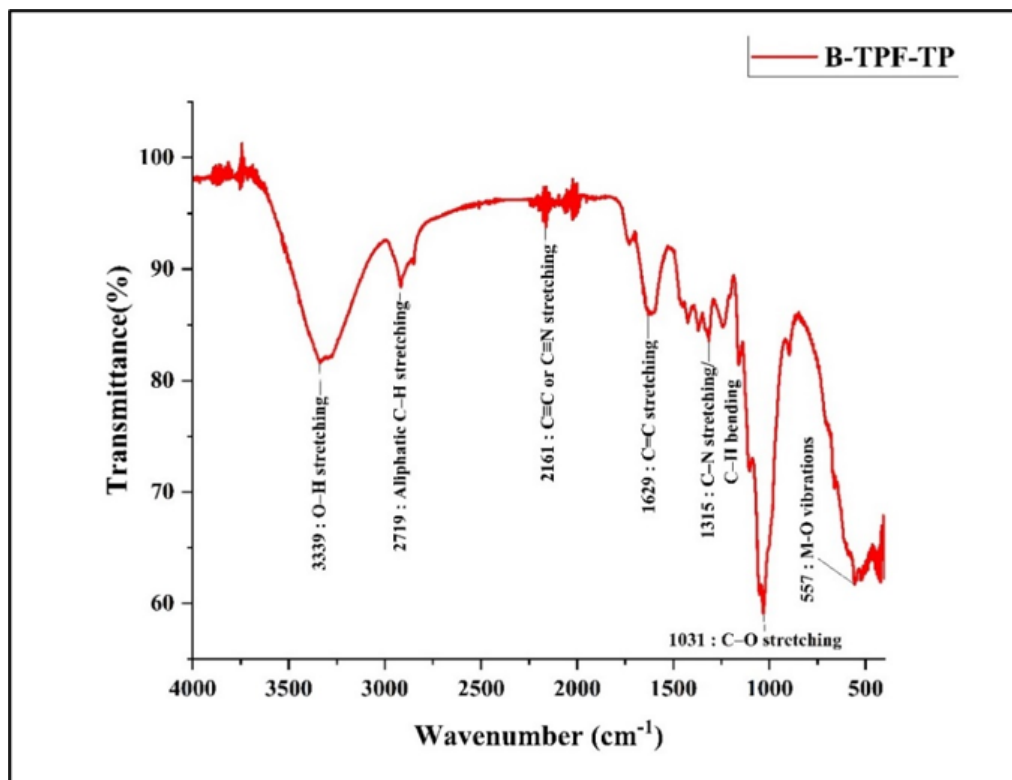


Fig. 1 b. FTIR analysis of *T. procumbens* Non-woven fabric treated with bitter melon seed powder.

XRD analysis

The phase nature behaviour of the *T. procumbens* nonwoven fabrics untreated and treated with nanoencapsulation of the *T. procumbens* leaf powder and Bitter “guard seed powder was studied by X-ray Diffraction (XRD) and the

corresponding patterns are given in Figure 2, 2a, 2b.

T. procumbens nonwoven fabric showed typical diffraction patterns. The diffraction pattern of the untreated fabric had a strong peak approximately at $2\theta \approx 22^\circ$, corresponding to the (200) plane of cellulose I, together with a broad diffraction band at lower angles (approximately $15-16^\circ$), which is attributed to the overlapping (1-10) and (110) planes.

Aslaner et al., (2021) designed nanofibers electrospun using grape seed extract along with rye flour, WPC, and PEO and crystalline nature was characterized by XRD analysis. The composite nanofiber exhibits both crystalline and amorphous features, demonstrating its semi-crystalline nature. The crystallinity of the PEO is responsible for the peaks at $2\theta = 19^\circ$ and $2\theta = 23^\circ$ in every sample.

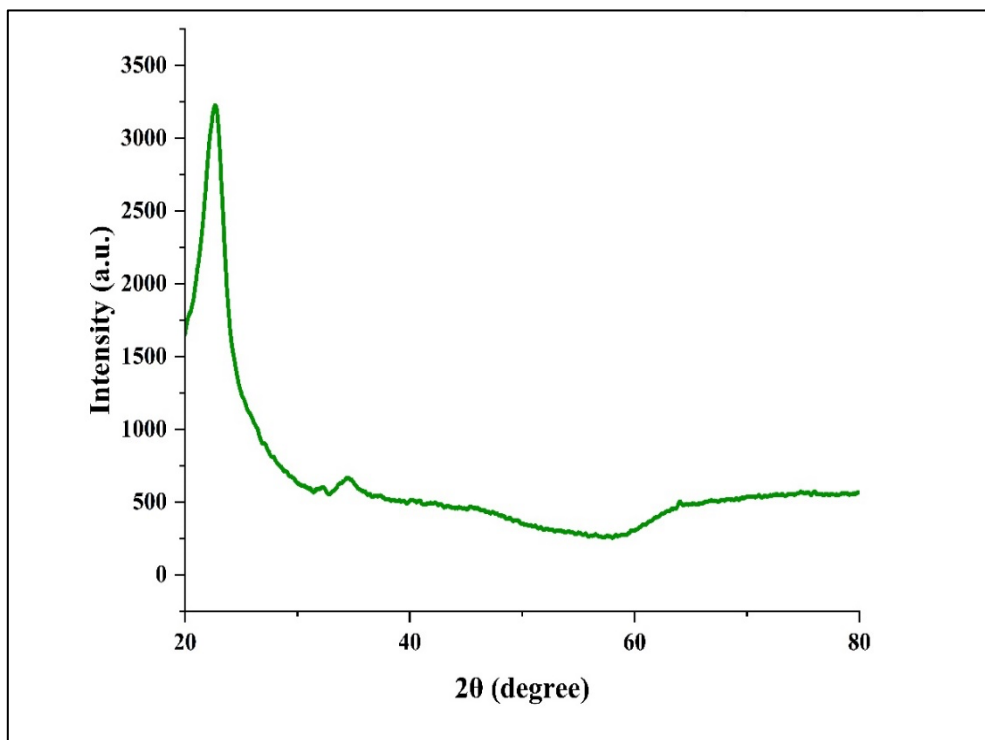


Fig. 2 XRD of *T. procumbens* untreated Non-woven Fabric

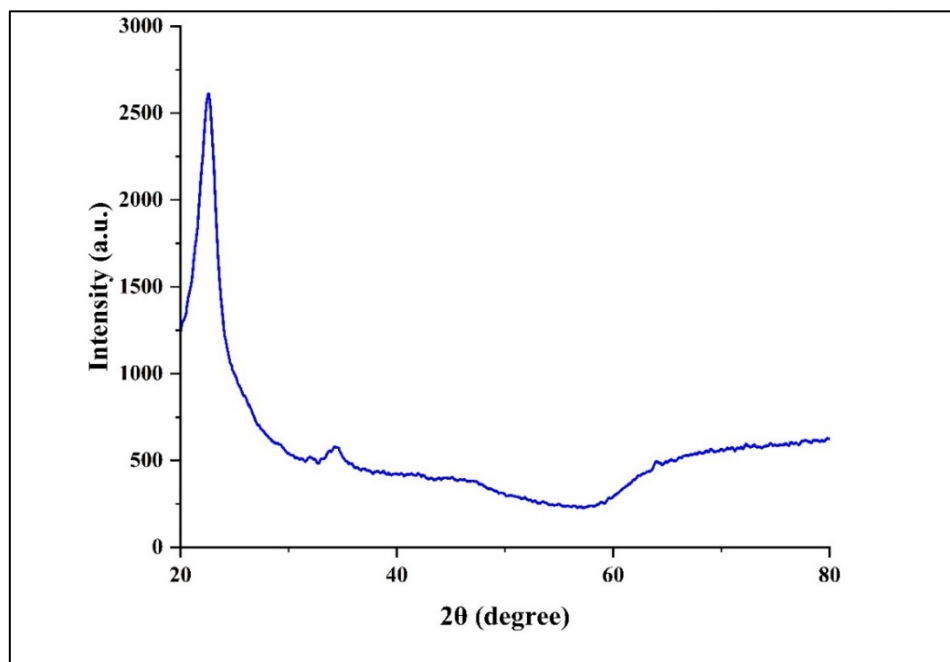


Fig. 2a XRD of *T. procumbens* Non-woven Fabric treated with *T. procumbens* leaf powder

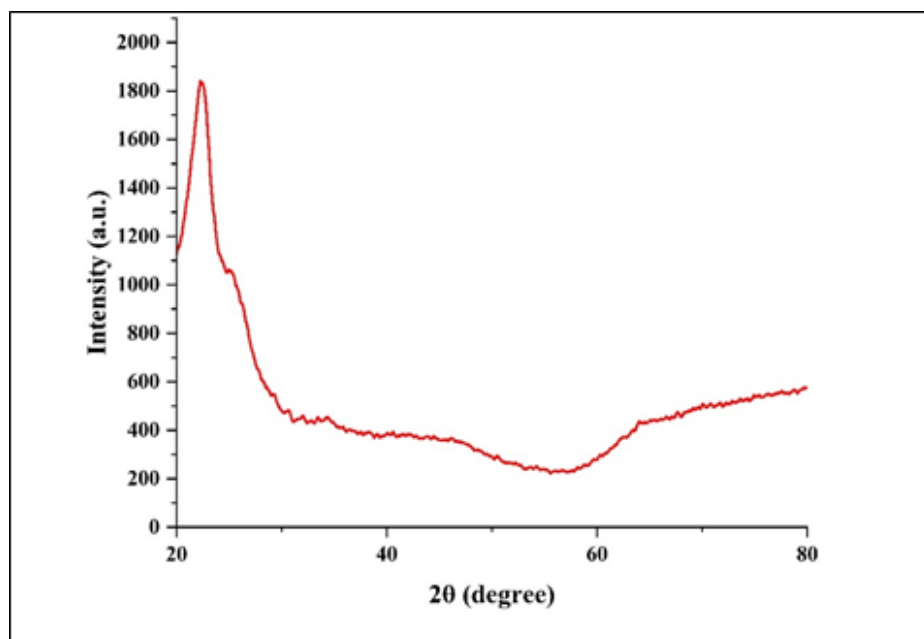


Fig. 2b XRD of *T. procumbens* Non-woven Fabric treated with bitter gourd seed powder.

TGA analysis :

The thermal stability of nonwoven fabrics of *T. procumbens* treated and untreated was analyzed by TGA. Thermograms of the analysis are illustrated in Fig. 3, 3a, and 3b. The untreated fibers showed the expected three-step degradation of lignocellulosic materials. The first degradation step, observed at temperatures below 120 °C, was attributed to volatilization of moisture and other components. Most of the degradation of the samples occurred at temperatures from 250 to 400 °C and was attributed to the decomposition of hemicellulose and cellulose. At higher temperatures, gradual decay of the samples was attributed to the decomposition of lignin and formation of a char. Nanoencapsulation of *T. procumbens* leaf powder and Bitter Gourd seed powder enhanced the thermal stability of *T. procumbens* nonwoven fabrics. The coating, as a barrier to thermal degradation, slowed and reduced the weight loss of the samples during the primary decomposition. The charred fabrics, especially the one treated with Bitter guard seed powder, remained a considerable amount of mass at elevated temperatures. This indicates enhanced thermal stability of the fabrics. This behaviour is likely the result of the presence of thermally stable phytochemicals, which include polyphenols, flavonoids, and other bioactive constituents. Carbonization and the inhibition of the diffusion of

volatile degradation products are facilitated by these phytochemicals. After finishing, no abnormal degradation or additional decomposition steps were observed, indicating that the nanoencapsulation procedure did not change the intrinsic thermal behaviour of the cellulose-rich fiber matrix. Instead, the herbal coating improved the thermal performance and retained the natural fibers structure. The thermal behaviour of *T. procumbens* nonwoven fabrics further demonstrates that the nanoencapsulation process can function on different lignocellulosic substrates. The enhancement of thermal stability due to functional finishing is beneficial for healthcare and diabetic shoe insole applications, where thermal stability and durability are essential.

Yilmaz et al. (2020) conducted an experiment of encapsulating a probiotic bacterium (*Lactobacillus paracasei* KS-199) with sodium alginate-based electrospun nanofiber mats and assessed the thermal stability using Thermogravimetric analysis. The thermogram shows first weight loss at 70 °C due to the loosely physisorbed water molecules, second weight loss of ~74 wt% in the range of 220–330 °C corresponds to the decomposition of PVA/SA side chains, and final weight loss of 14 wt % with decomposition at around 400 °C.

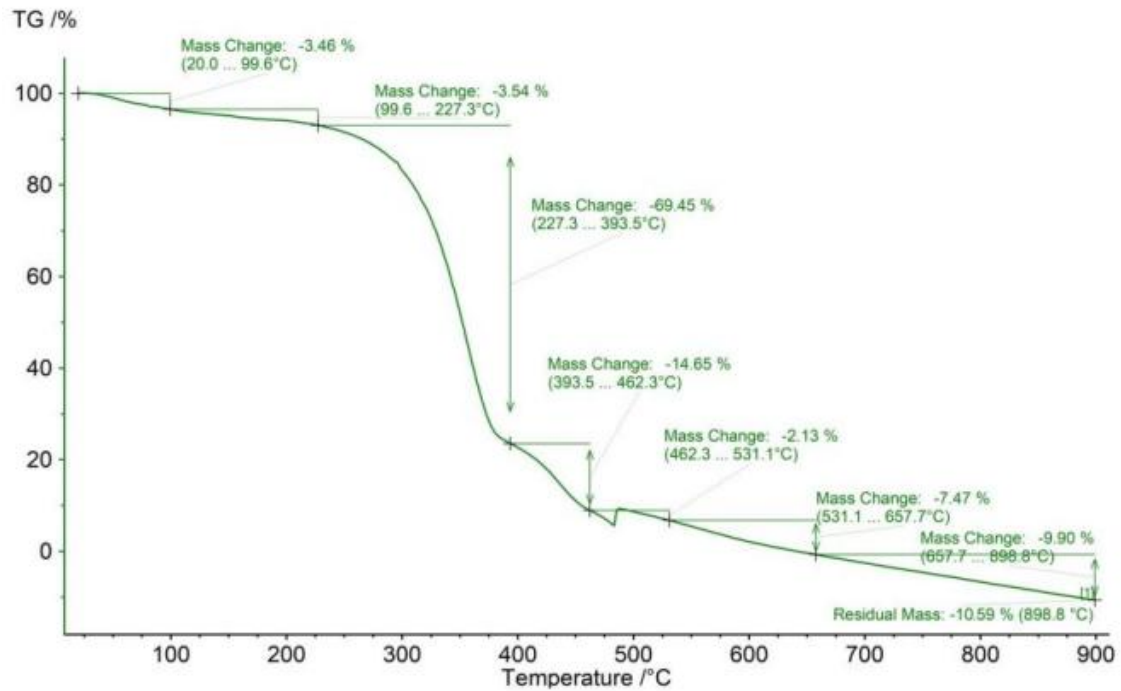


Fig. 3. TGA analysis of untreated *T. procumbens* Non-woven Fabric

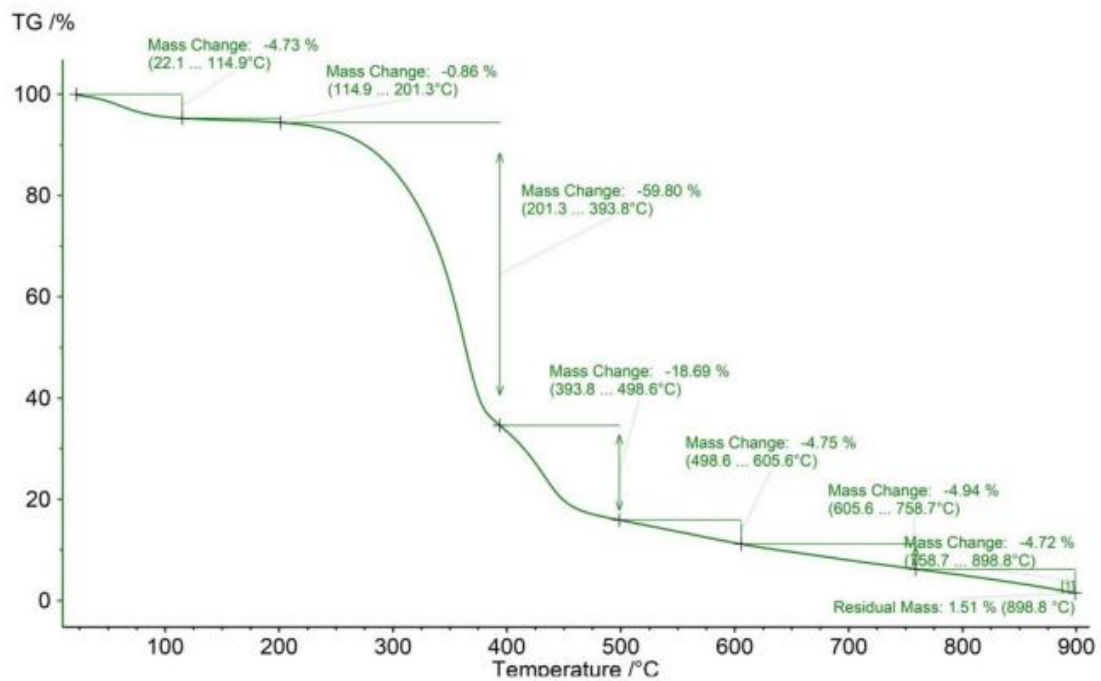


Fig. 3a. TGA analysis of *T. procumbens* Non-woven Fabric treated with *T. procumbens* leaf powder.

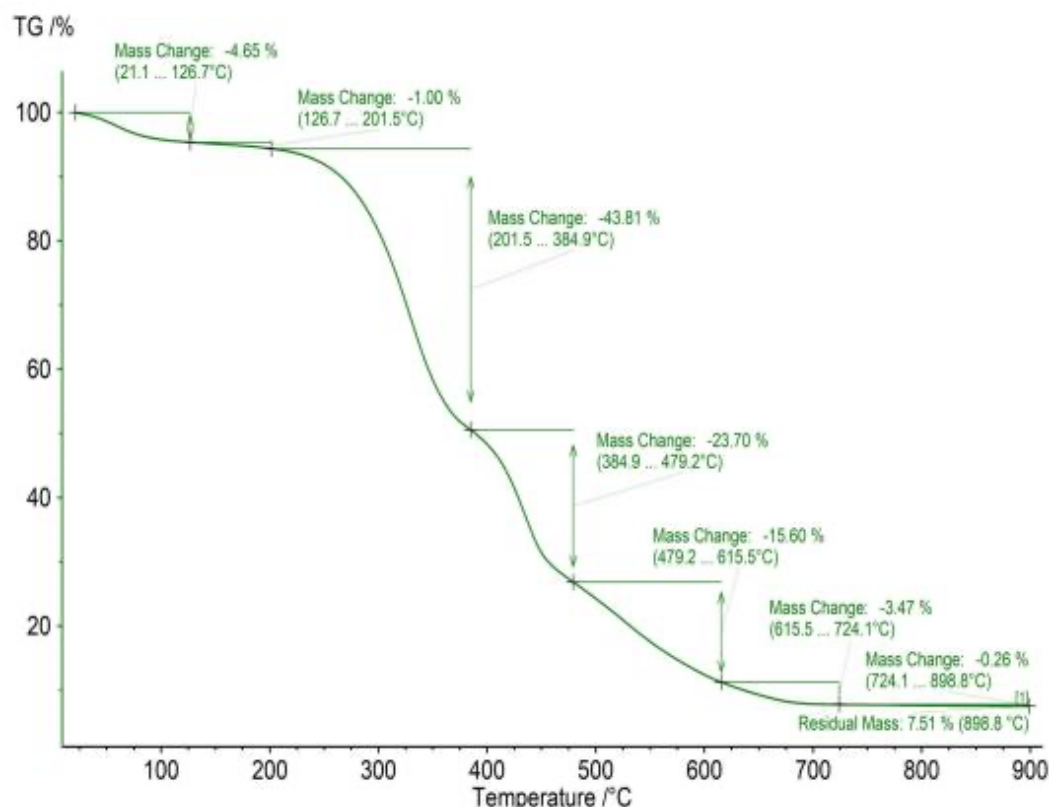


Fig.3b. TGA analysis of *T. procumbens* Non-woven Fabric treated with bitter gourd seed powder

FESEM Analysis:

Surface morphology of untreated and treated *T. procumbens* Non-woven fabrics coated with *T. procumbens* and Bitter gourd seed powder was analysed by FESEM. The images in Figure 4 show the *T. procumbens* fibres before the coating and how the treatment changed the surface of the fibres. *T. procumbens* fabric alone clearly shows the *T. procumbens* Fabric surface, which is uneven and has impurities. The surface of the fibres has longitudinal grooves, and some detached fibrils are still attached. At higher magnification, the fabric exhibited distinct fibrillar bundles and shallow cracks along the fiber axis. Both are established morphological traits of lignocellulosic fibers. These surface defects allow for numerous active sites for finishing treatments.

Following nano-encapsulation with *T. procumbens* leaf powder, significant morphological changes were noted in Fig.4a. The fiber became smooth and more compact, with partial closure of the longitudinal furrows. Deposited layers were uniformly distributed along the fiber surface. The natural fiber architecture was preserved, suggesting the herbal constituents were successfully adsorbed and anchored. The coating was uniform and continuous, indicating a good interaction of the encapsulated material with cellulose-rich fabric. More surface modification was noted for fabric treated with bitter gourd seed powder Fig. 4b. Compared to the untreated fabric, the Bitter gourd seed powder treated sample exhibited more compact deposits and a more continuous coating layer that spanned the longitudinal fibrils. The treated fibers exhibited less surface irregularity and a denser morphology coupled with retention of fiber integrity. A continuous coating confirmed the covalent immobilization of bioactive encapsulated particles on the fiber.

Ghayempour et al. (2026) conducted a study on in situ nanoencapsulation of essential oil-loaded alginate polymer on a cellulose cotton fabric for children's anorexia management. FESEM analysis reveals that the alginate polymer was stabilized on the cellulose fibers surface. The incorporation of essential oils in the network-like matrix of alginate was confirmed. The presence of emulsifier and coagulant salt has been confirmed by the uniform encapsulation.

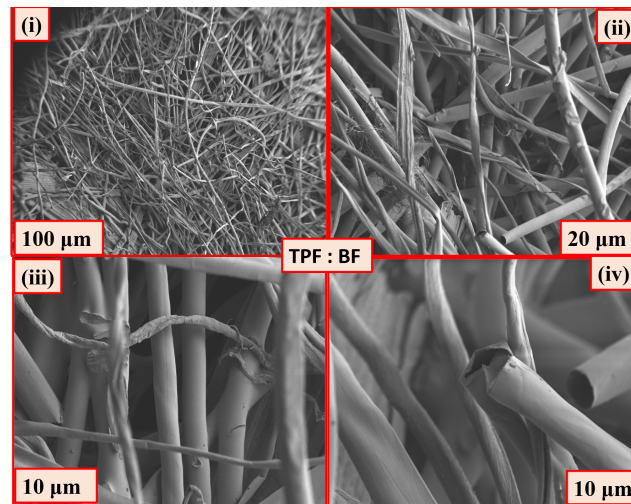


Fig. 4 FESEM analysis of *T. procumbens* untreated Non-woven Fabric.

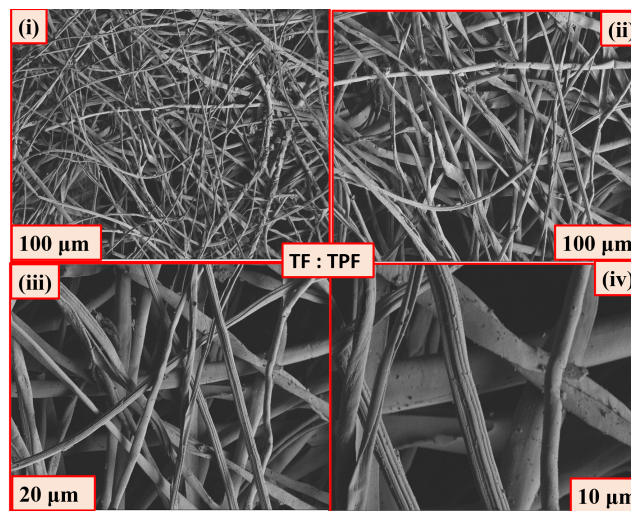


Fig. 4a. FESEM analysis of *T. procumbens* Non-woven Fabric treated with *T. procumbens* leaf powder.

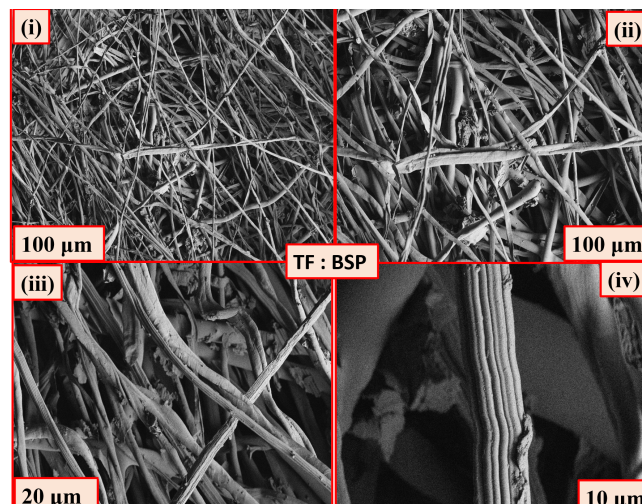


Fig. 4b. FESEM Analysis of *T. procumbens* Non-woven Fabric treated with Bitter gourd seed powder

Antibacterial activity: *Staphylococcus aureus* and *E. coli*.

The antibacterial “activity of the untreated and treated fabrics was evaluated against both *S. aureus* (Gram-positive) and *E. coli* (Gram-negative), and the results are shown in Fig.5 & 5a. *T. procumbens* nonwoven Fabric

untreated is not” showing any zone of inhibition. *T. procumbens* fabric treated with *T. procumbens* leaf powder shows a minimum zone of inhibition. *T. procumbens* fabric treated with Bitter gourd seed powder showed more inhibition.

Negi et al., (2022) synthesized chitosan nanoparticles and encapsulated with multiple essential oils followed by the evaluation of their antibacterial activity on various pathogens such as *L. monocytogenes*, *E. coli*, and *S. aureus* with Streptomycin as a control drug. It shows a

maximum inhibition zone of 17.5mm for *S. aureus*, whereas *E. coli* shows the lowest inhibition zone of 13.8mm for the chitosan nanoparticles encapsulated with lemongrass essential oil.

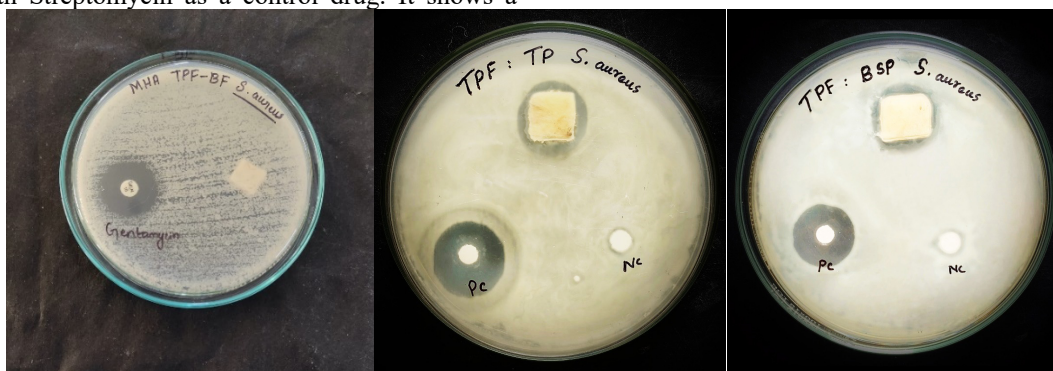


Fig. 5. Antibacterial activity against *S. aureus*

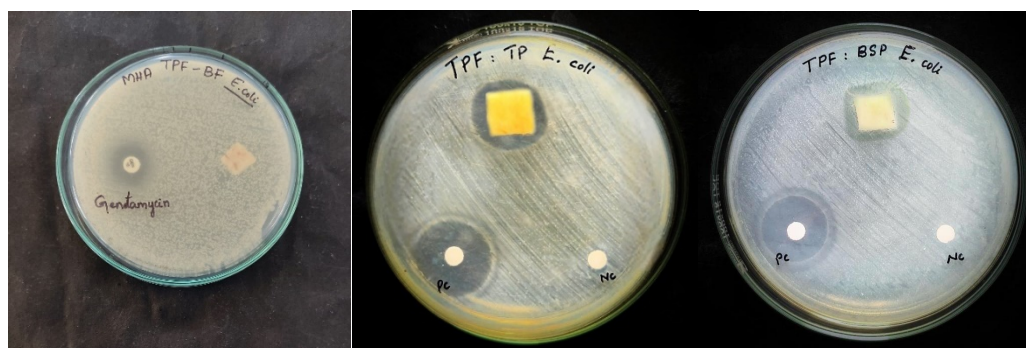


Fig. 5a. Antibacterial activity against *E. coli* analysis

Antifungal activity against *Aspergillus niger*:

The antifungal tests were conducted in accordance with the agar diffusion method. The results for both untreated and treated fabrics are shown in Figures 6. As for *T. procumbens* untreated fabrics, no antifungal activity was observed, and inhibition zones were absent or very small. The native *T. procumbens* fibers appear to lack sufficient antifungal activity to inhibit the growth of *A. niger*. The fungal mycelia grew profusely around the untreated fabric samples, proving the fibers are susceptible to fungal colonization. The nanoencapsulation finishing of *T. procumbens* fabric with *T. procumbens* leaf powder and Bitter gourd seed powder showed a significant increase in activity against *A. niger*, and an inhibition zone was clearly present around the fabric sample. Inhibition halos show that bioactive phytochemicals from the finishing process diffused into the surrounding medium and blocked the growth of fungi. This improved antifungal activity could be because of the inherent presence of phenolic compounds, terpenoids, alkaloids, tannins, and flavonoids.

The antifungal results of the finishing treatment of *T. procumbens* fabric confirmed improved activity against *A. niger*. The Bitter gourd seed powder finished fabrics also confirmed the developed bio-based finishing system. These results show the usable potential of treated *T. procumbens* nonwoven fabrics in many industries. Resistance to fungal contamination and control of microbial growth are especially useful in clothing, healthcare textiles, medical dressings, home furnishings, and protective textiles, making them useful in many applications.

Zhang et al. (2022) prepared a film using polyvinyl alcohol/ β -Cyclodextrin incorporated with *Zanthoxylum bungeanum* essential oil (ZBEO) via electrospinning fabrication. The antifungal activity was evaluated against *Botrytis cinerea*. After 7 days of incubation, the colony diameter of *Botrytis cinerea* was 30 mm, when treated with ZBEO nanofiber, inhibitory activity has been observed.



Fig.6 Antifungal activity against *A. niger*

Cytotoxicity analysis

Cytotoxicity of untreated and treated *T. procumbens* Non-woven fabrics coated with *T. procumbens* and Bitter gourd seed powder was analysed. When tested, untreated and treated fabric exhibited in vitro cytotoxicity using an MTT-based extraction textile assay and optical microscopic analysis of cellular morphology. In this study, polar (PBS) and non-polar (cottonseed oil) extracts were prepared according to the ISO 10993 standard. Representative micrographs for the *T. procumbens* nonwoven fabric systems are shown in Fig. 7. The control cultures (unprocessed) consisted of a confluent monolayer of healthy cells with well-developed cell polygons and cell membranes, and cell adhesion. The control was used as a standard in determining the cytotoxicity of the fabrics.

Yusefi et al. (2021) bio-nanofabricated a film “using chitosan and rice straw cellulose encapsulated 5-Fluorouracil (CS-CF/5FU BNCs) by the ionic gelation method with sodium tripolyphosphate (TPP) as a crosslinker. The cytotoxicity assay was conducted on the HCT116 CRC cancer cell line and CCD112 normal colon cell line. The results show that 15.62 µg/mL of chitosan nanoparticles was enough to eliminate $26.46 \pm 6.52\%$ of the CRC cells without any toxicity to the CCD112 normal cell line. Even at the highest concentration of 500 µg/mL, all the samples CF, CS NPs, and CS-CF BNCs showed biocompatibility without any damage to the normal” cells.

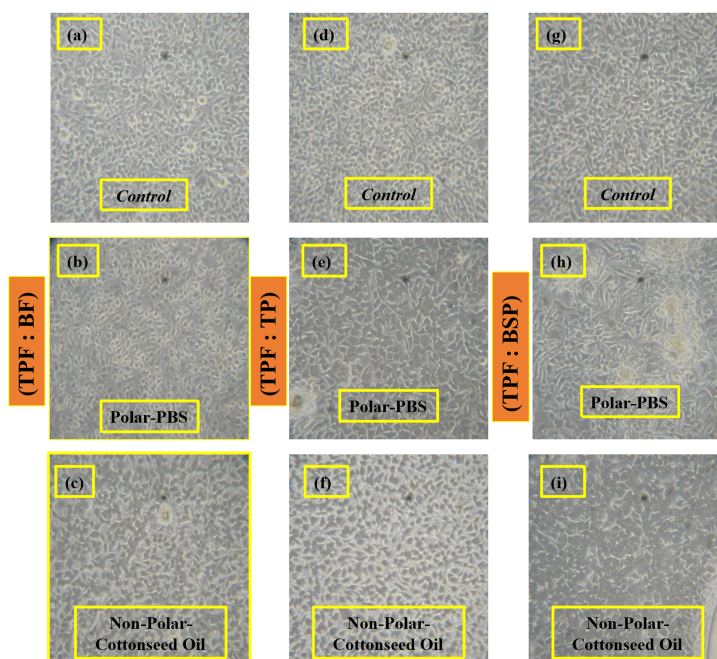


Fig. 7 Cytotoxicity analysis of TPF: BF, TPF: TP, TPF: BSP

CONCLUSION

The current research findings demonstrated that the bio-based functionalization of textile fabrics done by the herbal finishing approach has the ability to create antimicrobial and biocompatible textile fabrics. The developed nonwoven fabric referred to as *T. procumbens* was analysed in its untreated state, as well as treated with

Nano encapsulated *T. procumbens* leaf powder and Bitter gourd seed powder finishes. The functionalized fabric was evaluated both functionally and scientifically. The developed treatments clearly imparted anti-bacterial activity against *S. aureus* and *E. coli*. The treated fabrics also showed anti-fungal activity against *A. niger*. The anti-microbial activity and safety of the treated fabrics suggest

that these fabrics could be used for various applications in healthcare and hygiene, as well as in direct contact with the skin. Further studies at the composite level are required to verify the interfacial adhesion, durability, moisture resistance and long-term performance of the developed treatments. The bio-modified *T. procumbens* fibre, in combination with the developed finishing approach, can provide a lightweight, sustainable and chemically modifiable reinforcement for improving the mechanical properties of sustainable polymer composites, especially for non-load-bearing and semi-structural applications. Importantly, antimicrobial functionality was achieved without compromising the biological compatibility of the materials. The cytotoxicity assessment of extracts of *T. Procumbens* and Bitter gourd seed powder, is exposed to PBS, and cottonseed oil showed extracts retained normal morphology and cellular adhesion and maintained a monolayer. Only minor variations in cell density were noted in some of the treatment groups. A marked lack of cytotoxicity was observed for all the extracts. In particular, the Bitter gourd seed powder treated fabrics showed cellular behavior comparable to that of the respective controls. This showed that the bio-based finishing treatment did not show pronounced cytotoxic effects under the extraction conditions investigated. The combined antimicrobial and cytotoxicity results confirmed that the developed nanoencapsulation-finished fabrics provided a good balance of antimicrobial protection versus biological safety. The approach therefore offers a sustainable alternative to traditional textile finishing strategies where antimicrobial functionality and the ability to be in skin contact applications are required. The materials developed may find applications in healthcare and hygienic textiles, protective garments, wound-care materials, antimicrobial clothing, and other skin contact textile products. Overall, the results showed that the developed nanoencapsulation finishing strategy was highly flexible and offered an innovative approach to the production of multifunctional textiles that offer robust antimicrobial properties, while retaining the inherent biological safety of the textile substrate for Diabetic Shoe insoles.

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