

Article

Plasma-Assisted UV Grafting of Thermo-Responsive Chitosan-co-PNIPAAm Hydrogels on Polypropylene Nonwovens for Antibacterial Biomedical Textiles

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Abstract

Polypropylene (PP) nonwoven is widely used in biomedical textiles because of its lightweight and mechanical durability; however, its inherent hydrophobicity and chemical inertness limit further surface functionalization. In this study, a plasma-assisted UV grafting strategy was developed to fabricate thermo-responsive and antibacterial hydrogel coatings on PP nonwoven. Atmospheric-pressure plasma jet (APPJ) treatment was first employed to activate the PP nonwoven surface, followed by UV-induced graft polymerization of chitosan and *N*-isopropylacrylamide (NIPAAm), forming a chitosan-co-PNIPAAm hydrogel immobilized on the nonwoven substrate. Surface characterization using water contact angle measurement, Fourier transform infrared spectroscopy, and scanning electron microscopy confirmed effective plasma activation and successful hydrogel grafting. APPJ treatment significantly enhanced surface wettability, whereas subsequent UV grafting formed a continuous hydrogel on the PP nonwoven surface. The modified nonwoven exhibited distinct thermo-responsive swelling behavior in aqueous and simulated physiological environments, associated with the temperature-sensitive characteristics of the PNIPAAm component. In addition, the incorporation of chitosan imparted pronounced antibacterial activity against *Escherichia coli*, with inhibition zone diameters ranging from 14 to 16.5 mm, indicating high antibacterial sensitivity. Preliminary cytocompatibility evaluation further demonstrated favorable cell viability on the modified surfaces. This study demonstrates a scalable and low-temperature surface engineering approach for integrating stimuli-responsive and antibacterial hydrogel functionality into nonwoven polymer substrates, offering potential for advanced biomedical textile applications.

Keywords: polypropylene nonwoven; atmospheric-pressure plasma jet; UV-induced graft polymerization; thermo-responsive hydrogel; chitosan; antibacterial



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1. Introduction

Polypropylene (PP) nonwoven fabrics are ubiquitous in biomedical and healthcare-related textiles owing to their lightweight nature, mechanical robustness, chemical stability, and cost-effectiveness [1,2]. These advantages make PP nonwoven fabrics ideal candidates for disposable medical products, wound dressing, and protective textiles [2–4]. However, the intrinsic hydrophobicity and chemical inertness of PP nonwoven significantly

restrict its surface functionalization, limiting its ability to interact effectively with biological environments or integrate advanced functionalities, such as bioactivity and stimuli-responsiveness [5,6]. Therefore, surface modification has become a critical strategy for expanding the applicability of PP nonwoven-based materials without compromising their bulk mechanical properties [3,7]. Among various surface engineering techniques, plasma treatment has been extensively employed to activate polymer surfaces. Atmospheric-pressure plasma jet (APPJ) processing offers several advantages, including low-temperature operation, solvent-free processing, and high efficiency, making it suitable for temperature-sensitive nonwoven substrates [8–10]. The APPJ treatment can introduce reactive species and oxygen/nitrogen-containing functional groups, which serve as essential initiation sites for subsequent chemical grafting on inert surfaces [8–10].

A particularly pressing challenge in clinical nursing is the prevention and management of pressure ulcers (bedsores), which are often exacerbated by accumulated body heat and local moisture at the skin-textile interface. This is especially true for patients who stay in bed and move very little. The skin is in constant contact with the fabrics. This contact lasts for several hours every day. The heat and moisture remain in the same area. Problems begin when the skin is wet for too long. The skin becomes softer and easier to damage. Normal protective function is no longer robust. In this situation, bacteria can grow without difficulty. Infections are more likely to occur, and healing also requires more time. Many wound dressings used today are made of polymeric nonwoven materials. These materials are mainly used to cover wounds, separating the wound from the outside. However, these dressings do not respond to the events occurring at the wound site. For example, the temperature changes are not controlled, moisture is not removed effectively, and bacteria are not actively suppressed. Therefore, new types of polymeric dressings are being developed for handling heat in a more controlled way, monitoring moisture more effectively, and reducing bacterial growth on wound surfaces.

The integration of stimuli-responsive hydrogels with nonwoven substrates is a promising solution. Stimuli-responsive hydrogels have attracted considerable attention due to their ability to undergo reversible physicochemical changes in response to external stimuli, including temperature, pH, and ionic strength [11–13]. Among them, poly(*N*-isopropylacrylamide) (PNIPAAm) is one of the most extensively studied thermo-responsive polymers, exhibiting a lower critical solution temperature (LCST) of approximately 32–34 °C, which closely matches human skin temperature [13–17]. Below the LCST, PNIPAAm-based networks are highly hydrated and swollen, whereas above the LCST, polymer chains collapse due to enhanced hydrophobic interactions, leading to water expulsion and altered permeability [13–18]. PNIPAAm changes its state when the temperature is close to body temperature. This change can occur many times and is reversible. For this reason, PNIPAAm hydrogels have been used in various biomedical applications, including drug delivery, tissue engineering, and wound dressings. In most cases, its temperature responses to the environment are fully developed and skillfully designed.

Chitosan (CS), a derived polysaccharide obtained from the deacetylation of natural chitin, has been widely incorporated into biomedical materials owing to its biocompatibility, biodegradability, and inherent antibacterial activity [19–24]. The presence of protonated amino groups allows chitosan to interact electrostatically with negatively charged bacterial cell membranes, providing a non-leaching antibacterial mechanism that is especially desirable for long-term wound care. In addition, chitosan exhibits pH-responsive swelling behavior, which is highly relevant given that infected or chronic wounds often present elevated pH values compared with healthy skin [18,23]. Consequently, chitosan not only contributes antibacterial functionality but also enhances the environmental responsiveness of wound dressing materials. The combination of chitosan with thermo-responsive polymers,

such as PNIPAAm, has emerged as an effective strategy for fabricating multifunctional hydrogels that integrate environmental responsiveness with biological activity [13,18,25,26]. However, most reported chitosan-PNIPAAm systems are prepared as bulk hydrogels, films, or loosely attached to coatings [25–28]. These configurations often suffer from insufficient mechanical robustness, poor adhesion to fibrous substrates, or limited durability under repeated deformation, which restrict their practical implementation in medical textiles. Moreover, achieving uniform and covalent immobilization of multifunctional hydrogels onto chemically inert PP nonwoven fibers while preserving breathability, flexibility, and mechanical integrity remains a significant technical challenge.

In this study, a plasma-assisted UV graft polymerization strategy was proposed to fabricate thermo-responsive and antibacterial hydrogel coatings on PP nonwovens. The APPJ treatment was first applied to activate the PP nonwoven surface, followed by UV-induced graft polymerization of chitosan and *N*-isopropylacrylamide to form a chitosan-co-PNIPAAm hydrogel network covalently immobilized on the nonwoven substrate. The surface chemistry, wettability, and morphology of the modified PP nonwoven were evaluated at different temperatures and simulated physiological environments. Furthermore, the antibacterial performance and cytocompatibility of the modified surfaces were assessed to demonstrate their potential in biomedical textile applications. This study provides a practical and scalable surface engineering approach for integrating stimuli-responsive hydrogel functionality with polymeric nonwoven substrates, thereby offering insights into the design of smart and bioactive polymeric textiles.

2. Materials and Methods

2.1. Pretreatment of Materials

PP nonwoven (18 g/m²) was provided by the Taiwan Textile Research Institute (New Taipei City, Taiwan) and sectioned into 1 × 1 cm². The PP nonwoven was industrially fabricated via a thermal bonding (hot-pressing) process in air, which may induce slight surface oxidation or leave trace amounts of oxygen-containing additives on the PP nonwoven. The PP nonwoven substrates were ultrasonically cleaned sequentially in mild detergent solution, ethanol, and deionized (DI) water for 15 min each to remove surface contaminants and residual organic species. After cleaning, the samples were dried in an oven at 40 °C overnight before surface modification. All materials were handled with clean gloves throughout the pretreatment and subsequent experiments to minimize the risk of contamination. All chemical reagents were purchased from Sigma-Aldrich (St. Louis, MO, USA) and used as received without further purification, including medium-molecular-weight chitosan (CS), *N*-isopropylacrylamide (NIPAAm, C₆H₁₁NO, Mw = 113.16 g/mole), ammonium persulfate (APS, (NH₄)₂S₂O₈, Mw = 228.20 g/mole), *N,N'*-methylenebisacrylamide (NMBA, C₇H₁₀N₂O₂, Mw = 154.17 g/mole), *N,N,N',N'*-tetramethylethylenediamine (TEMED, C₆H₁₆N₂, Mw = 116.24 g/mole), and Vitamin B₂ (Mw = 376.36 g/mole, C₁₇H₂₀N₄O₆). The chitosan used in this work (Sigma-Aldrich) had a reported degree of deacetylation of approximately 75–85%, a viscosity of 200–800 cP (1 wt% in 1% acetic acid), and an ash content below 2%, according to the supplier's specifications.

2.2. Atmospheric Pressure Plasma Jet Surface Activation

Atmospheric-pressure plasma jet (61G20, ae Plasma 41 Co., Ltd., Taoyuan City, Taiwan) treatment was applied to activate the surface of the PP nonwoven substrates before UV graft polymerization. The plasma system was equipped with a rotating jet head (Φ = 35 mm) driven by an AC power supply. During APPJ treatment, the PP nonwoven substrates were mounted on a motorized moving stage and translated through the plasma discharge region at a fixed linear speed of 20 mm/s. To ensure uniform surface exposure, adjacent scanning

paths were arranged with partial overlap, allowing homogeneous plasma treatment over the entire PP nonwoven surface. Argon was used as the working gas at a constant flow rate of 20 slm (standard liter per minute), and the operating power was set to 300 W. The distance between the plasma nozzle and the substrate surface was fixed at 10 mm. The plasma treatment duration varied (30 s, 60 s, and 120 s) to investigate the effect of plasma exposure on surface activation. All the treatments were performed at atmospheric pressure and ambient temperature to avoid thermal damage to the PP nonwoven substrates. The APPJ process introduced reactive species and polar functional groups (e.g., -OH and RNS) onto the inert PP nonwoven surface, thereby enhancing surface reactivity and facilitating subsequent UV-induced graft polymerization.

2.3. Thermo-Responsive Chitosan-co-PNIPAAm Hydrogel on PP Nonwoven Surfaces by UV Light Surface-Induced Graft Polymerization

All sample solutions were prepared using deionized water. For the grafting precursor, a CS solution with a concentration of 3 wt% was first prepared in a dilute acetic acid solution. This solution was then mixed with a 5 wt% NIPAAm solution at a volume ratio of 2:1. To enable controlled free-radical polymerization and hydrogel network formation, the precursor solution was supplemented with 1 mol% APS as initiator, 5 mol% NMBA as the crosslinking agent, and 1 mol% TEMED as accelerator based on NIPAAm monomer. In addition, 0.05 mol% Vitamin B₂ (riboflavin) was used to assist the photoinitiation process. The volume ratio of the monomer precursor solution to the riboflavin solution was kept at 4:1. Plasma-activated PP nonwoven substrates were placed in a Pyrex Petri dish and immersed in the prepared mixed solution. The samples were then exposed to UV light to induce grafting. The UV wavelength was 365 nm, and the nominal output power was 1000 W, positioned at an approximate distance of 8 cm from the sample surface. The irradiation intensity at the sample surface was estimated to be approximately 800 mW/cm², based on the lamp specifications and working distance. The irradiation time was 5 min. During UV irradiation, the reaction was carried out in a circulating water bath set at 4 °C. The continuous water circulation was used to remove excess heat generated by the UV lamp and to keep the reaction temperature stable, thereby preventing overheating of the samples. Following grafting, the samples were thoroughly rinsed with DI water and soaked overnight to remove residual monomers and non-covalently bound polymers. The grafted PP nonwoven samples were subsequently dried at room temperature before further analysis. Figure 1 illustrates the preparation of surface-modified PP nonwovens.

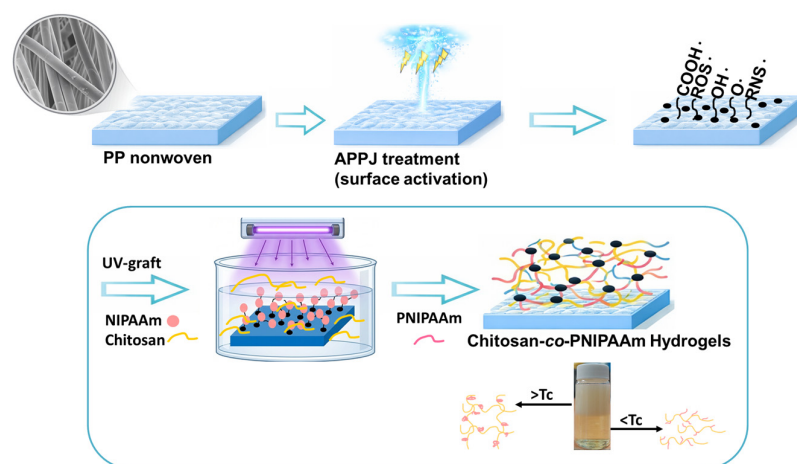


Figure 1. Schematic illustration of the surface functionalization process, involving APPJ pretreatment followed by UV-induced graft polymerization of a thermo-responsive Chitosan-co-PNIPAAm hydrogel onto the PP nonwoven substrate.

2.4. Characterizations

2.4.1. Wettability (Surface Hydrophobicity/Hydrophilicity)

The surface wettability and hydrophilicity of the pristine and modified PP nonwoven samples were evaluated by water contact angle (WCA) measurements using the sessile drop method. A deionized water droplet with a fixed volume of 0.9 μL was deposited onto the sample surface to minimize the effects of gravity on the droplet shape. The contact angles were captured and analyzed at room temperature using a digital microscope system (Dino-Lite, AnMo Electronics Corporation, Hsinchu City, Taiwan) and a Dino Capture 2.0. To ensure statistical reliability, measurements were performed at three distinct locations on each specimen, and the results were reported as average values ($n = 3$). The measurements on fibrous substrates may be influenced by the interstitial spaces between fibers. Therefore, the WCA measurements were used as a qualitative indicator to verify the surface transition from hydrophobic to hydrophilic.

2.4.2. Surface Morphology and Structure Characterization

The surface morphology and chemical composition of the PP nonwoven samples were characterized to verify the success of surface modification. The topographical changes in the fibrous structure before and after modification were examined using a field-emission scanning electron microscope (FE-SEM, JEOL JSM-6701F, Tokyo, Japan). Owing to the non-conductive nature of the polymer substrates, the specimens were sputter-coated with platinum for 30 s before observation to enhance the surface conductivity and prevent charging effects. Simultaneously, the chemical structure changes on the PP nonwoven surfaces were analyzed using attenuated total reflection Fourier-transform infrared spectroscopy (ATR-FTIR, Jasco FTIR-6200, Tokyo, Japan) in the wavenumber range of 4000–400 cm^{-1} . This analysis identified the characteristic functional groups introduced by the plasma activation and subsequent UV graft polymerization.

2.4.3. Swelling Behavior of Grafted Thermo-Responsive Hydrogels on PP Nonwoven Surfaces

The swelling behavior of the chitosan-co-PNIPAAm grafted PP nonwoven substrates was evaluated gravimetrically to determine their thermo-responsive characteristics. Before the swelling tests, the modified samples were dried to a constant weight, and their initial dry weights (W_0) were recorded. The specimens were then immersed in either deionized water or simulated body fluid (SBF) and incubated at controlled temperatures of 25 $^{\circ}\text{C}$ or 37 $^{\circ}\text{C}$ to simulate ambient and physiological conditions. At predetermined time intervals, the swollen samples were removed from the medium, gently blotted with a filter paper to remove excess surface liquid, and weighed (W_s). The swelling measurements were performed until equilibrium was reached. The swelling ratio (SR) was calculated using the following equation:

$$SR(\%) = \frac{W_s - W_0}{W_0} \times 100\%. \quad (1)$$

2.4.4. In Vitro Cytocompatibility Evaluation

The cytocompatibility of the modified PP nonwoven samples was evaluated using an in vitro cell viability assay with NIH-3T3 mouse embryonic fibroblast cells (Bioresource Collection and Research Center, Hsinchu, Taiwan). This study did not involve live animals or human subjects. The NIH-3T3 cells used in this study were commercially obtained cell lines; therefore, ethical approval was not required. The relative cell viability was quantified using the Alamar Blue assay, which monitored the metabolic activity of live cells through the reduction of resazurin to resorufin. Before cell seeding, the modified PP nonwoven specimens were sterilized by exposure to UV light from a biosafety cabinet for 24 h, and

then placed into uncoated 24-well culture plates under aseptic conditions. NIH-3T3 cells are cultured in Dulbecco's modified Eagle medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 100 U/mL penicillin–streptomycin–amphotericin. Cells were seeded directly onto the sample surfaces at a density of 3×10^4 cells/mL and incubated in a humidified incubator containing 5% CO₂ at 37 ± 0.5 °C. Cell viability was assessed after 1, 3, 5, and 7 days of culture. At each time point, Alamar Blue reagent was added to each well, and the plates were incubated at 37 ± 0.5 °C for 4 h in the dark [29]. The absorbance was measured at 570 nm using a microplate reader. Cell viability was expressed as the mean $\pm$ standard deviation of three independent measurements ($n = 3$). Cytocompatibility tests were performed on selected plasma-treated and hydrogel-grafted samples (30 s and 60 s plasma pretreatments) based on representative surface-modification conditions.

2.4.5. Antibacterial Activity Test

The antibacterial activity of the modified PP nonwoven samples was evaluated using the disk diffusion method (Kirby–Bauer-type assay). *Escherichia coli* (*E. coli*, ATCC 25922) was obtained from the Bioresource Collection and Research Center (BCRC, Hsinchu, Taiwan) and was used as a model gram-negative bacterium. The bacterial culture was grown in nutrient broth at 37 °C for approximately 17 h with shaking at 250 rpm to reach the exponential phase. The bacterial suspension was adjusted to a concentration of approximately 1×10^7 CFU/mL and uniformly spread onto agar plates. The modified and unmodified PP nonwoven samples were cut into circular specimens with a diameter of 10 mm and placed on the surface of the inoculated agar plates. Pristine PP nonwoven was used as the negative control for antibacterial tests. The plates were incubated at 37 °C for 8, 12, and 24 h. The antibacterial activity was assessed by measuring the diameter of the inhibition zone surrounding each sample. The presence of a clear inhibition zone indicated the susceptibility of the bacteria to the modified surfaces, whereas the absence of an inhibition zone indicated no detectable antibacterial effect. All antibacterial experiments were performed in triplicate, and the inhibition zone diameters were reported as the mean $\pm$ standard deviation.

3. Results and Discussion

3.1. Wettability of Surface-Modified PP Nonwoven Samples

The surface wettability of untreated and surface-modified PP nonwoven samples was evaluated by WCA measurements and water absorption behavior analysis. As summarized in Table 1, the untreated PP nonwoven exhibited an apparent WCA of $83.6 \pm 2.4^\circ$, confirming the hydrophobic nature of the PP nonwoven substrate.

Table 1. Wettability of pristine and surface-modified PP nonwoven samples.

Sample	Water Contact Angle (°)	Water Absorption Time (s)
PP nonwoven	83.6 ± 2.4	17.2
APPJ-treated PP nonwoven	— [†]	<1
APPJ + UV-chitosan-co-PNIPAAm (30 s)	48.5 ± 1.1 *	<5
APPJ + UV-chitosan-co-PNIPAAm (60 s)	42.4 ± 2.8 *	<5
APPJ + UV-chitosan-co-PNIPAAm (120 s)	39.5 ± 1.6 *	<5

Statistical significance was evaluated by one-way ANOVA followed by Dunnett's test. $p < 0.05$ (*) compared with pristine PP nonwoven. [†] Water droplets rapidly spread and penetrated the porous nonwoven structure upon deposition, preventing reliable contact angle determination.

After APPJ treatment, the surface wettability of the PP nonwoven was markedly enhanced. Water droplets deposited on the plasma-treated samples spread rapidly and

penetrated the fibrous structure in less than 1 s, resulting in an apparent contact angle approaching 0° (complete wetting). This behavior is attributed to the combined effects of the plasma-induced surface polar groups and capillary wicking arising from the porous, nonwoven architecture. Therefore, for plasma-only treated samples, the WCA measurements primarily reflect qualitative changes in wettability rather than the absolute surface energy values. Following UV-induced graft polymerization of chitosan-co-PNIPAAm hydrogels, the modified PP surfaces exhibited apparent contact angles ranging from $48.5 \pm 1.1^\circ$ to $39.5 \pm 1.6^\circ$, depending on the plasma pretreatment time. Compared with the plasma-only treated samples, the grafted hydrogel layer regulated the rate of water penetration into the nonwoven structure, leading to more stabilized droplet profiles that allowed quantitative comparison. The observed decrease in the contact angle with increasing plasma treatment time suggests enhanced grafting efficiency and increased surface coverage of the hydrophilic hydrogel network. Despite these differences in the contact angle values, all modified samples exhibited rapid water absorption (<5 s), indicating significantly improved wettability relative to pristine PP nonwoven. These results demonstrate that APPJ activation followed by UV-induced grafting effectively modified the surface wetting behavior of PP nonwoven, transitioning the substrate from a hydrophobic surface to a highly wettable and functionally regulated interface suitable for biological applications.

3.2. FTIR Characterization of Surface-Modified PP Nonwoven Samples

Figure 2 shows the ATR-FTIR spectra of pristine PP nonwoven, APPJ-treated PP nonwoven (120 s), and APPJ + UV-chitosan-co-PNIPAAm grafted samples. The pristine PP nonwoven exhibits characteristic absorption bands at approximately $2950\text{--}2840\text{ cm}^{-1}$, corresponding to C-H stretching vibrations of the polypropylene backbone, consistent with its hydrophobic behavior observed in the WCA measurements. Yet, moderate absorption peaks in the carbonyl region are observed, which are attributed to the thermo-oxidation on the surface induced during the industrial thermal bonding (hot-pressing) process conducted in air. Such superficial contributions do not represent the intrinsic chemical structure of the PP and do not indicate the presence of amide groups. After APPJ treatment, the appearance and increased intensity of absorption bands in the range of $1700\text{--}1600\text{ cm}^{-1}$ can be attributed to the introduction of oxygen-containing functional groups, such as carbonyl (C=O) species, generated during plasma-induced surface oxidation. These newly introduced functional groups serve as reactive sites for subsequent graft polymerization. Following UV-induced grafting of the chitosan-co-PNIPAAm hydrogel, additional absorption bands become evident. The bands observed at approximately 1650 cm^{-1} and 1540 cm^{-1} are assigned to amide I (C=O stretching) and amide II (N-H bending) vibrations, respectively, confirming the successful incorporation of PNIPAAm and chitosan components. A broad absorption band in the region of $3200\text{--}3500\text{ cm}^{-1}$ is also observed, which is associated with overlapping O-H and N-H stretching vibrations from the hydrogel network. Moreover, the intensity of these characteristic hydrogel-related bands increases with increasing plasma pretreatment time from 60 s to 120 s, indicating enhanced grafting efficiency. The FTIR analysis confirmed that APPJ treatment facilitated surface oxidation and enabled the successful grafting of the chitosan-co-PNIPAAm hydrogel onto the PP nonwoven surface. After APPJ activation and UV-induced graft polymerization, additional spectral features associated with oxygen and nitrogen-containing functionalities become discernible, consistent with the enhanced wettability and regulated water uptake behavior discussed above. However, due to the limited thickness of the modified surface and the penetration depth of ATR-FTIR, the spectra remain dominated by the characteristic absorption bands of the original PP nonwoven.

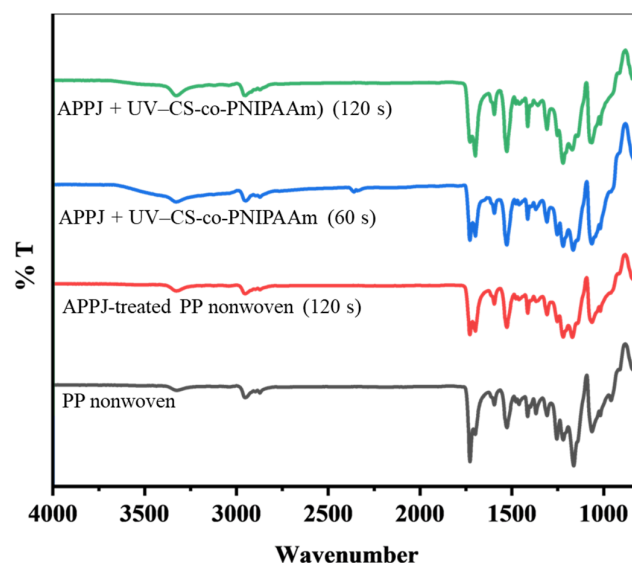


Figure 2. FTIR spectra of pristine PP nonwoven, APPJ-treated PP nonwoven (120 s), and APPJ + UV-chitosan-co-PNIPAAm grafted samples prepared with plasma pretreatment times of 60 s and 120 s.

3.3. SEM Morphology of Surface-Modified PP Nonwoven Samples

Figure 3 shows the surface morphology of the pristine and surface-modified PP nonwoven samples observed by scanning electron microscopy (SEM). The pristine PP nonwoven sample is shown in Figure 3a. It exhibits a typical fibrous network with smooth fiber surfaces and clear inter-fiber voids, which are characteristics of melt-blown PP nonwoven structures. Figure 3b–d shows PP nonwoven samples after APPJ treatment for 30, 60, and 120 s. The fibrous structure is present in all cases. The fibers do not show melting or fusion. No obvious damage is observed. The fiber surfaces appear slightly rougher than those of pristine PP. Compared to the pristine sample, the plasma-treated fibers exhibited slightly increased surface roughness and subtle textural changes, which can be attributed to plasma-induced surface etching and oxidation. Table 2 shows the elemental composition data obtained from the EDS analysis. The pristine PP nonwoven fabric has an oxygen content of 23.07 wt%, verifying the introduction of surface carbonyl group during the preparation of this PP nonwoven by further hot-pressing. After plasma treatment, the carbon content decreases. The oxygen content increases with treatment time. For example, the oxygen content increases to 30.47 wt% after 120 s of plasma treatment. Nitrogen is also detected after plasma exposure.

These surface modifications are expected to enhance surface reactivity and provide active sites for subsequent graft polymerization. Figure 3e–g shows the PP nonwoven sample after UV-induced grafting of CS-co-PNIPAAm hydrogel. The fiber surfaces are no longer smooth. A layer can be seen on the fibers. Some of the open spaces between fibers become connected by this layer. The EDS data after grafting show further changes. The carbon content decreases to 53.92–57.86 wt%. The oxygen content increases to 35.02–39.17 wt%. Notably, the nitrogen content increased to approximately 7 wt% for all grafted samples. Nitrogen is barely present in the PP nonwoven. Therefore, this increase is due to the grafted hydrogel with the incorporation of nitrogen-containing chitosan and PNIPAAm chains. Moreover, the gradual increase in oxygen and nitrogen contents with increasing plasma pretreatment time (30–120 s) indicates that enhanced surface activation promotes more effective grafting of the hydrogel. Samples treated with longer plasma times show slightly higher oxygen and nitrogen contents after grafting. This suggests that plasma pretreatment affects the grafting behavior. The overall structure of the nonwoven is still maintained after grafting.

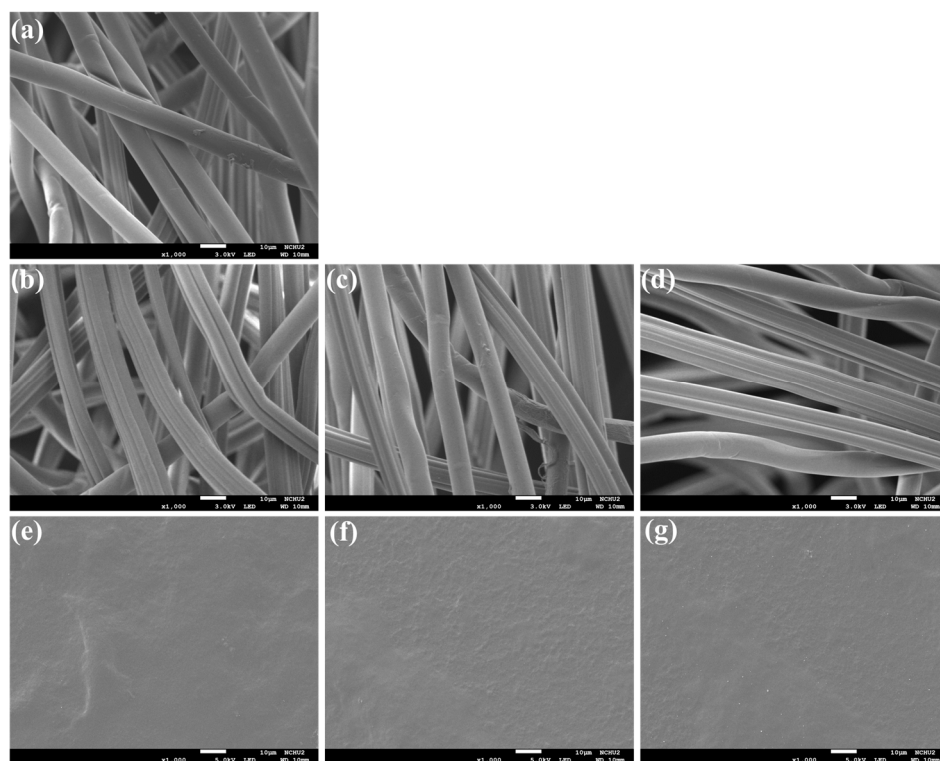


Figure 3. SEM images of pristine and surface-modified PP nonwoven samples (a) pristine PP nonwoven; (b–d) APPJ-treated PP nonwoven APPJ-treated PP nonwoven samples under progressively increased plasma treatment conditions (30 s, 60 s, 120 s); and (e–g) chitosan-co-PNIPAAm hydrogel grafted PP nonwoven samples were prepared with increasing plasma pretreatment (30 s, 60 s, and 120 s) before UV-induced graft polymerization.

Table 2. EDS elemental composition (wt%) of pristine and surface-modified PP nonwoven.

Sample	Weight Concentration (%)		
	C	N	O
PP nonwoven	75.11	1.82	23.07
APPJ-treated PP nonwoven (30 s)	70.68	4.06	26.28
APPJ-treated PP nonwoven (60 s)	66.96	4.72	28.32
APPJ-treated PP nonwoven (120 s)	64.51	5.02	30.47
APPJ + UV-chitosan-co-PNIPAAm (30 s)	57.86	7.12	35.02
APPJ + UV-chitosan-co-PNIPAAm (60 s)	54.18	7.27	38.55
APPJ + UV-chitosan-co-PNIPAAm (120 s)	53.92	6.91	39.17

Although the hydrogel layer partially bridges the inter-fiber voids, the layer remains thin and does not block the overall porous structure. The nonwoven substrate, therefore, retains its flexibility and permeability. Based on the combined SEM and EDS results, a thin and continuous chitosan-co-PNIPAAm hydrogel layer is successfully formed on the PP fibers without destroying the original fibrous architecture.

3.4. Swelling Behavior of Hydrogel-Grafted PP Nonwoven Samples

Table 3 lists the equilibrium swelling ratios of pristine and surface-modified PP nonwoven samples. The measurements were carried out in deionized water and simulated body fluid (SBF). Two temperatures were selected, 25 °C and 37 °C. The pristine PP nonwoven and the APPJ-treated PP nonwoven show relatively high swelling ratios. This is because of its porous fiber structure, which can absorb a lot of water through capillary action. The values do not change much at 25 °C and 37 °C. Different results are observed for the

APPJ + UV-chitosan-*co*-PNIPAAm hydrogel samples. These samples show lower swelling ratios due to the grafted hydrogel layer covering the surface, though the hydrogel is hydrophilic. The hydrophilic hydrogel can absorb water but restrain water from entering the pores of the PP nonwoven, thereby leading to lower swelling ratios. The swelling behavior also changes with temperature. For the hydrogel-grafted samples, the swelling ratios at 37 °C are lower than those at 25 °C. This trend is observed in both deionized water and SBF. This behavior is related to the temperature response of PNIPAAm. When the plasma pretreatment time is increased, the swelling ratio becomes lower, indicating enhanced grafting density and more effective hydrogel network formation. This trend suggests that longer plasma treatment affects the grafting process and the hydrogel structure. These results confirm that the swelling behavior of the modified PP nonwoven is governed by the thermo-responsive hydrogel rather than by the PP nonwoven substrate itself.

Table 3. Equilibrium swelling ratios of pristine and surface-modified PP nonwoven samples measured in DI water and SBF at 25 °C and 37 °C. All values are reported as mean $\pm$ standard deviation ($n = 3$).

Sample	Deionized Water, 25 °C (%)	Deionized Water, 37 °C (%)	SBF, 25 °C (%)	SBF, 37 °C (%)
PP nonwoven	92.23 $\pm$ 0.25	97.14 $\pm$ 0.23	94.21 $\pm$ 0.18	92.45 $\pm$ 0.13
APPJ-treated PP nonwoven (30 s)	94.36 $\pm$ 0.38	98.29 $\pm$ 0.16	97.34 $\pm$ 0.29	96.78 $\pm$ 0.34
APPJ-treated PP nonwoven (60 s)	95.56 $\pm$ 0.13	98.46 $\pm$ 0.14	97.56 $\pm$ 0.38	97.23 $\pm$ 0.23
APPJ-treated PP nonwoven (120 s)	97.44 $\pm$ 0.34	98.32 $\pm$ 0.17	98.15 $\pm$ 0.24	98.68 $\pm$ 0.28
APPJ + UV-chitosan- <i>co</i> -PNIPAAm (30 s)	73.0 $\pm$ 0.24 *	75.76 $\pm$ 0.23 *	76.73 $\pm$ 0.21 *	80.34 $\pm$ 0.19 *
APPJ + UV-chitosan- <i>co</i> -PNIPAAm (60 s)	68.46 $\pm$ 0.24 *	72.39 $\pm$ 0.35 *	78.56 $\pm$ 0.23 *	77.53 $\pm$ 0.13 *
APPJ + UV-chitosan- <i>co</i> -PNIPAAm (120 s)	65.31 $\pm$ 0.12 *	74.74 $\pm$ 0.23 *	81.36 $\pm$ 0.14 *	80.92 $\pm$ 0.35 *

Statistical significance was evaluated by one-way ANOVA followed by Dunnett's test. $p < 0.05$ (*) compared with pristine PP nonwoven under the same medium and temperature conditions.

3.5. Cytocompatibility Evaluation of Surface-Modified PP Nonwoven Samples

The cytocompatibility of the pristine and surface-modified PP nonwoven samples was evaluated using NIH-3T3 fibroblasts, and the results are presented in Figure 4. Cell viability was assessed using the Alamar Blue assay after 1, 3, 5, and 7 days of incubation. As shown in Figure 4, all tested samples exhibited cell viability comparable to or higher than that of pristine PP nonwoven throughout the culture period, indicating that neither APPJ treatment nor subsequent CS-*co*-PNIPAAm hydrogel grafting induced any detectable cytotoxic effects. Pristine PP nonwoven showed stable cell viability over time, serving as a suitable reference substrate.

Compared to pristine PP, the APPJ-treated samples (30 s and 120 s) exhibited slightly enhanced cell viability, particularly at extended culture times. This improvement can be attributed to plasma-induced surface activation, which increases surface wettability and promotes favorable cell–surface interactions. Importantly, no adverse effects on cell viability were observed after plasma treatment under the tested conditions. Furthermore, the PP nonwoven samples grafted with CS-*co*-PNIPAAm hydrogels demonstrated consistently stable cell viability at all time points. The presence of the hydrogel layer did not compromise cytocompatibility and, in some cases, resulted in a higher cell viability than that of untreated PP nonwoven. This behavior is likely associated with the hydrophilic and biocompatible nature of chitosan-containing polymer networks, which provide a favorable microenvironment for cell attachment and proliferation.

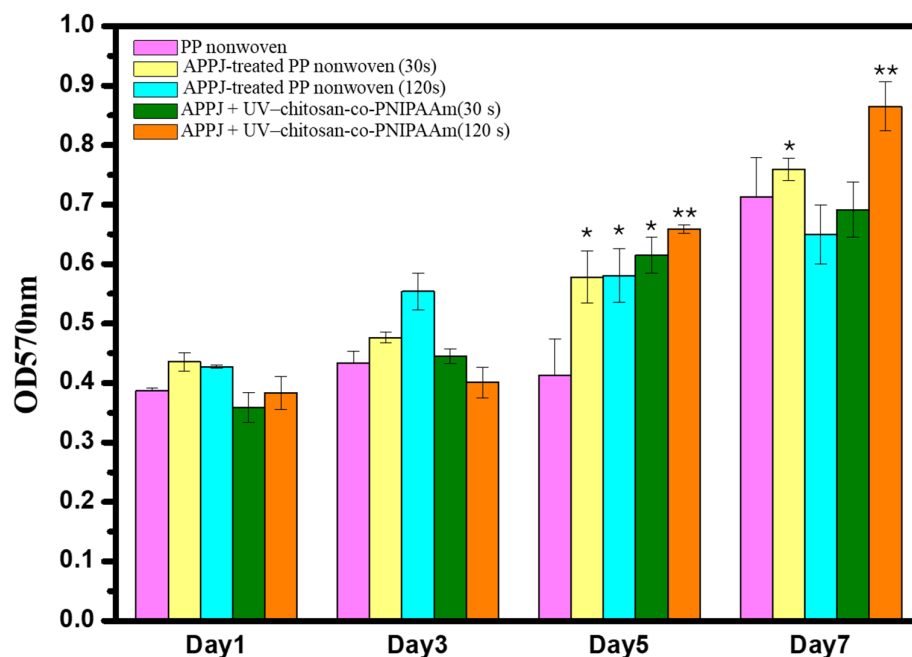


Figure 4. Cell viability of NIH-3T3 fibroblasts cultured on pristine and surface-modified PP nonwoven samples was evaluated using the Alamar Blue assay after 1, 3, 5, and 7 days of incubation. The samples included pristine PP nonwoven, APPJ-treated PP nonwoven (30 s and 120 s), and CS-co-PNIPAAm grafted PP nonwoven prepared with plasma pretreatment of 30 s and 120 s. Data are presented as mean $\pm$ standard deviation ($n = 3$). Statistical significance was evaluated by one-way ANOVA followed by Dunnett's test. $p < 0.05$ (*), $p < 0.01$ (**) compared with untreated PP nonwoven at the same time point.

The cytocompatibility results confirmed that the surface modification strategy employed in this study preserved the biocompatibility of the PP nonwoven substrates. The combination of plasma activation and hydrogel grafting yields a cytocompatibility surface suitable for potential biomedical textile applications.

3.6. Antibacterial Activity of Surface-Modified PP Nonwoven Samples

The antibacterial activity of pristine and surface-modified PP nonwoven samples against *Escherichia coli* was evaluated using a disk diffusion (Kirby-Bauer-type) assay at 37 °C, and representative inhibition zone images are shown in Figure 5. The pristine PP and plasma-treated PP nonwoven samples exhibited negligible inhibition zones, indicating their limited intrinsic antibacterial activity.

In contrast, the PP nonwoven samples grafted with CS-co-PNIPAAm hydrogels exhibited clear inhibition zones at all examined time points, confirming the effective antibacterial functionality imparted by the chitosan-containing hydrogel. The presence of inhibition zones demonstrates that the surface modification strategy successfully endowed the PP nonwoven with antibacterial properties. The quantitative analysis of the inhibition zone diameters is summarized in Table 4, showing that hydrogel-grafted samples consistently exhibited larger inhibition zones than the untreated and plasma-treated groups. The diameter of the inhibition zone gradually decreased with increasing incubation time from 8 to 24 h. This time-dependent behavior is attributed to the contact-based and diffusion-limited antibacterial mechanisms of the surface-grafted hydrogel, rather than the continuous release of antibacterial agents. As the incubation proceeded, bacterial regrowth at the periphery of the inhibition zones resulted in a reduction in the apparent zone diameter, which is commonly observed in surface-mediated antibacterial systems. The enhanced antibacterial performance of the grafted samples is primarily associated with the functional contribution

of chitosan to the polymer network. The positively charged chitosan component interacts with the negatively charged bacterial cell membranes, thereby inhibiting bacterial growth near the modified surface.

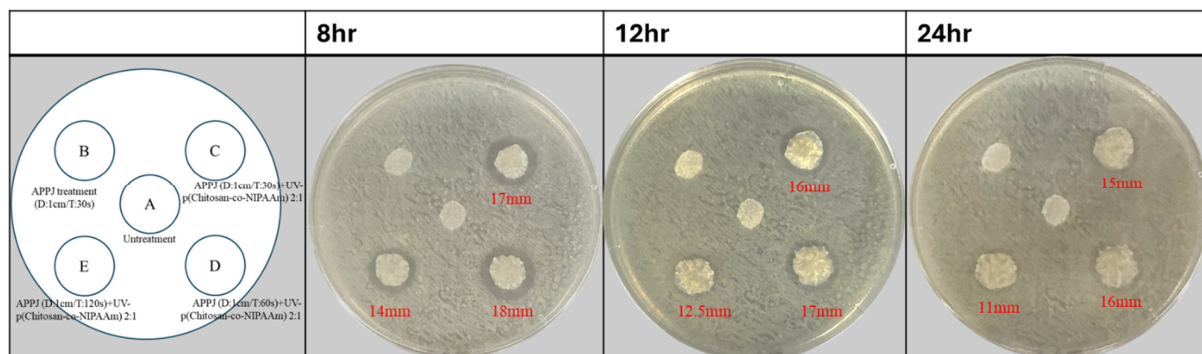


Figure 5. Antibacterial activity of pristine and surface-modified PP nonwoven samples against *E. coli* evaluated by a disk diffusion (Kirby–Bauer-type) assay at 37 °C. Inhibition zones were recorded after 8, 12, and 24 h of incubation. The decrease in inhibition zone size over time reflects the contact-based and diffusion-limited antibacterial behavior of the surface-modified samples.

Table 4. Antibacterial activity against *E. coli* (mean $\pm$ SD, $n = 3$).

Sample	8 h (mm)	12 h (mm)	24 h (mm)
Pristine PP nonwoven	0	0	0
APPJ-treated PP nonwoven (30 s)	0	0	0
APPJ + UV-chitosan-co-PNIPAAm (30 s)	17.0 $\pm$ 0.8	16.0 $\pm$ 0.8	15.0 $\pm$ 0.7
APPJ + UV-p(CS-co-NIPAAm) (60 s)	18.0 $\pm$ 0.9	17.0 $\pm$ 0.2	16.0 $\pm$ 0.2
APPJ + UV-p(CS-co-NIPAAm) (120 s)	14.0 $\pm$ 0.7	12.5 $\pm$ 0.7	11.0 $\pm$ 0.6

Values are expressed as mean $\pm$ standard deviation ($n = 3$). “0” indicates no observable inhibition zones.

Overall, these results demonstrated that the CS-co-NIPAAm hydrogel grafted PP nonwoven samples provided effective short-term antibacterial protection at physiological temperatures. Such surface-mediated antibacterial behavior is particularly relevant for biomedical textile applications, where immediate suppression of bacterial adhesion and early-stage colonization are desired.

4. Conclusions

In this study, a plasma-assisted UV grafting strategy was successfully developed to functionalize PP nonwoven surfaces with a thermo-responsive CS-co-NIPAAm hydrogel. APPJ treatment effectively activated the chemically inert PP nonwoven surface, generating reactive sites that enabled subsequent UV-induced graft polymerization of a chitosan-based thermo-responsive hydrogel.

Surface characterization confirmed the successful surface modification at each processing stage. The FTIR and SEM-EDS analyses revealed the introduction of oxygen-containing functional groups after the plasma treatment and the appearance of characteristic amide bands after hydrogel grafting, indicating effective incorporation of chitosan and PNIPAAm components. SEM observations demonstrated that the surface modification was uniform and conformal, while preserving the intrinsic fibrous morphology and structural integrity of the PP nonwoven substrate. As a result, the surface-modified samples exhibited markedly enhanced wettability, transitioning from an intrinsically hydrophobic surface to a highly wettable interface with rapid liquid uptake.

Swelling ratio studies revealed that the hydrogel grafted PP nonwoven exhibited regulated, medium, and temperature-dependent swelling behavior. Compared to DI water,

samples immersed in SBF displayed more stable swelling profiles, and reduced swelling was observed at physiological temperature (37 °C), consistent with the thermo-responsive nature of the PNIPAAm component. The combination of rapid wetting and controlled equilibrium swelling is particularly advantageous for maintaining a balanced moisture environment in biomedical textile applications.

Moreover, the hydrogel grafted PP nonwoven samples demonstrated effective surface-mediated antibacterial activity against *E. coli* at 37 °C, whereas pristine and plasma-treated PP nonwoven samples showed negligible antibacterial effects. The antibacterial performance is attributed to the presence of chitosan within the grafted hydrogel network and is characterized by a contact-based, diffusion-limited mechanism. Cytocompatibility evaluation using NIH-3T3 fibroblasts confirmed that the surface modification strategy did not induce detectable cytotoxic effects, indicating the good biocompatibility of the modified PP nonwoven surfaces.

The results of this study demonstrate that plasma-assisted grafting of CS-co-PNIPAAm hydrogels provides an effective and versatile approach for imparting multifunctionality to PP nonwoven substrates, including improved wettability, regulated swelling, antibacterial activity, and cytocompatibility while preserving the desirable bulk properties of the nonwoven structure. This surface modification strategy shows strong potential for biomedical textile applications, particularly in wound dressings and related healthcare materials, where moisture management, infection control, and biocompatibility are critical.

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