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A Novel Material Nano-Scale Material Derived from Garlic Shell Integrated with Red Meat Samples

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Abstract

The study aimed to develop a novel garlic-shell-based nanofiber using electrospinning and to evaluate its effectiveness in enhancing the safety and shelf life of red meat coated with the fabricated nanofibers. The fabricated nanofibers (71.869 ± 52.830 nm) were characterized by Scanning Electron Microscopy (SEM), Fourier Transform Infrared (FTIR) spectroscopy, and Thermogravimetric Analysis (TGA). FTIR spectra of the fabricated nanofibers revealed a chemical structure featuring hydroxyl, aliphatic, and carbonyl groups, alongside active sulphur compounds such as allicin. The thermal mass loss of the obtained nanofibers was not significant at the cooking temperature of red meat samples. The treatment significantly suppressed the growth of pathogenic and spoilage microorganisms ($p < 0.05$). The nanofibers achieved a maximum log reduction of 0.885 for *Escherichia coli* by day 11. *Salmonella typhimurium* decreased by 0.66 log CFU/g in red meat samples treated with garlic-shell nanofibers compared with non-nanotreated red meat samples stored at 4°C. Besides pathogenic microorganisms, a significant suppression of Total Psychrophilic Bacteria was observed, ending at 5.10 log CFU/g compared to 6.30 log CFU/g in control samples (decline: 1.2 log CFU/g). On the other hand, the decline in Total Aerobic Mesophilic Bacteria growth was found to be 0.54 log CFU/g over an 11-day analysis period. The findings suggested that nanofibers fabricated from garlic shell, a kind of food waste, represent a promising, bio-based alternative for active food packaging, capable of enhancing the microbiological safety and extending the refrigerated shelf-life of red meat products. Thus, this novel application could play an important role in further food applications.

1. Introduction

Novel approaches are being explored globally to address current challenges across various industrial sectors, particularly by scientists and manufacturers. In the last decade, microscale material treatments have received considerable attention. Currently, nanoscale applications, ranging from the food industry to the healthcare sector, have been utilized (Tylingo et al., 2016; Ceylan & Meral, 2023). In this context, in addition to nanoparticles and nanoemulsions, nanoliposomes and nanofibers are critical alternatives to other scale materials (Govindappa et al., 2021; Ceylan et al., 2020). Recent reviews and research-based studies indicate that nanofibers provide a larger surface contact area on the material, which can be coated or entrapped (Mousavipour et al., 2021; Zhou et al., 2023). Thus, these studies indicate that different materials, such as bio-based ones (curcumin, nisin, rosemary, thyme, and carvacrol, etc.), in nanoscale form may present antimicrobial, anticancerogenic, and antioxidative effects (Meral et al., 2019; Niaz et al., 2019; Campolo et al., 2020; Gayathri et al., 2023). Therefore, the industry has begun to investigate these novel types of material in the scope of the issues mentioned above. In this sense, molecular characterization and thermal properties should be studied in particular to determine the properties of the fabricated nanoscale materials. Furthermore, food treatments with nanoscale materials are gaining increasing importance day by day. In some studies, it is clearly mentioned that nanoscale materials such as nanoparticles and nanoemulsions can successfully improve the shelf-life of fish and red cheese stored at cold temperatures, because these materials efficiently delay microbiological spoilage, as well as chemical, physical, and sensory deterioration of food materials (Hoque et al., 2020;

Delshadi et al., 2021; Ceylan et al., 2024). To illustrate, in addition to total mesophilic bacteria growth, some pathogenic microorganisms (*Salmonella* and *E. coli*, etc.) can be detected in foods. So, some novel approaches based on nanotechnology should address these kinds of pathogenic microorganisms to improve food safety and keep human health. With the above-mentioned important issues, the investigation or revealing of cytotoxicity of fabricated nanoscale materials can increase the reliability of the use of the obtained nanofibers. In this regard, recently published studies have revealed that nanofibers obtained from carvacrol, cellulose, and zein-eugenol possessed anticancer and cytotoxic properties, as stated by Tibolla et al. (2019), Ceylan et al. (2024), and Ceylan et al. (2025).

The present study aimed to fabricate a garlic-based nanofiber material, as demonstrated by significant analysis. The second aim was to characterize the fabricated electrospun nanofiber material using SEM, FTIR, and TGA. The final goal of the present study was to investigate the potential limitations of the fabricated nanofibers on the growth of total mesophilic and psychrophilic bacteria, as well as *Salmonella* and *E. coli*, found in foods. Therefore, the study was mainly aimed at presenting an alternative nano-scale material approved via the tests above, especially for industrial applications.

2. Materials and Methods

2.1. Materials

2.1.1. Garlic Plant Procurement and Extraction

Garlic peels (*Allium sativum L.*) were collected from the outer parts that were not in direct contact with the garlic. After being washed, the collected peels were dried at 35°C for 10 hours and then ground. The ground garlic powder was prepared with a 1/1 ratio of ethanol/water (v/v) to 2.5% (w/v) and mixed at 300 rpm for 15 hours. At the end of this period, the supernatant was separated by centrifugation at 1500 rpm for 10 minutes.

2.1.2. Red Meat Tenderloin Supply

Red meat tenderloin is sourced from freshly slaughtered beef (Eastern Anatolian red) from a clean commercial operation in the central district of Bingöl province.

2.1.3. Consumables

Plate Count Agar PCA, 105463.0500, Merck, was used for the enumeration of total aerobic mesophilic (TAMBS) and psychrophilic bacteria. TBX (Tryptone Bile X-glucuronide) agar (Merck 1.16122) was used for the enumeration of *Escherichia coli*. XLD (Xylose Lysine Deoxycholate) agar, 105287, Merck, was used for the enumeration of *Salmonella typhimurium*. Petri Dish was ISOLAB - P.S - Ø90 x 17 mm.

2.2. Methods

2.2.1. Electrospinning procedures

Electrospinning was performed using benchtop electrospinning equipment. The equipment consisted of a high voltage source (0–30 kV, 0–1.0 mA, Faraday Electric and Electronics Ltd., Erzurum), a syringe pump (Harvard Apparatus 11 Plus, Holliston, Massachusetts, USA), and a 20x20 stainless steel collector plate. The electrospinning solution was prepared by mixing 10% PVA with garlic peel extract at a ratio of 3/1 for 2 h at 300 rpm. Electrospinning conditions were 0.250 ml/h flow rate, 10 cm collector plate distance, and 10.75 kV electrical power. The prepared solution was tested at flow rates of 0.100–1.5 ml/h, with an electrical power of 8–25 kV, and with a distance between the needle and the collector plate of 8–20 cm to optimize nanomaterial production. The nanomaterial produced in 30 minutes was collected on aluminium or wax paper and coated onto red meat samples. The coated red meat samples were stored at 4 ± 2°C for quality assessment on days 1, 3, 5, 7, 9, and 11.

2.2.2. Scanning Electron Microscopy (SEM)

SEM (Scanning Electron Microscope, Zeiss Sigma 300) analysis was performed at Van Yuzuncu Yil University Science Application and Research Center (BAUM). The morphologies of the fabricated nanofiber by lavender were revealed using scanning electron microscopy (SEM) with magnifications of 100, 50, and 20 KX, respectively. The electrospun nanofiber samples were detected under low vacuum in a field emission SEM (distance: 8 mm and voltage 5 kV). The diameters in fabricated nanofibers were calculated as stated by Hotaling et al. (2015).

2.2.3. TGA Analysis

TGA analyses were performed by measuring the weight loss of approximately 15 mg of nanoencapsulated material under a nitrogen atmosphere, increasing the temperature from room temperature by 10°C per minute to 600°C. Calcium oxalate monohydrate was used for calibration of the instrument (TG/DTG/DTA-DSC, SII Nanotechnology, EXSTAR 7300).

2.2.4. FTIR Analysis

FTIR analyses were conducted at the Ağrı İbrahim Çeçen University Central Research and Application Laboratory Center (MERLAB). An FTIR (Thermo Scientific Nicolet IS10, ATR-FT-IR) instrument was used in the study. FTIR results were measured by using an FT-IR spectrometer attached with the ATR diamond module by Bruker Optics (Germany) in the range of 400 and 4000 cm^{-1} (resolution of 4 cm^{-1}).

2.2.5. *Salmonella typhimurium*

25 g of test samples was taken and digested in 225 mL of peptone water (Merck 1.07214, 0.1%) using a stomacher device (HG400VW, Wiggens, Straubenhardt, Germany). The required dilutions (10^4-10^7 CFU/mL) were prepared from the mixture and inoculated onto XLD (Xylose Lysine Desoxycholate) Agar (Merck 1.05287), which is specific for *Salmonella typhimurium*. After 24 hours of incubation at 37°C, colonies with the same colour as the medium, translucent, and sometimes having a black center were counted as *Salmonella typhimurium* (Wenke, 2009; ISO 6887-1: 2017).

2.2.6. *Escherichia coli*

10 g of test samples was taken and digested in 90 mL of peptone water (Merck 1.07214, 0.1%) using a stomacher device (HG400VW, Wiggens, Straubenhardt, Germany). The required dilutions (10^3-10^6 CFU/mL) were prepared from the mixture and inoculated onto TBX (Tryptone Bile X-glucuronide) agar (Merck 1.16122), which is specific for *Escherichia coli*. After 24 hours of incubation at 44°C, blue-green colonies were counted as *Escherichia coli* (TS ISO 16649-2, 2012; Pol-Hofstad and Jacobs-Reitsma, 2021).

2.2.7. Total mesophilic bacteria and count

Total mesophilic bacteria count (TMABC) was determined as stated by the FDA's Bacteriological Analytical Manual method described via FDA-BAM (FDA, 2001). The PCA: plate colony counting was used to determine the number of TMAB. Ten g red meat sample from red meat samples (control: non-nanofiber and red meat parts treated with garlic-based nanofibers) was separately homogenized for 150 s by a stomacher IU Instruments (Spain). Up to 10^7 (diluted samples) were spread on agar (PCA: plate count, Merck-VM888763 930, Darmstadt, Germany) and incubated for 48 h at 35°C. For Total Psychrophilic Bacteria (TPB) growth, the serial dilutions (up to 10^7 CFU/mL) were prepared and then incubated at 7°C for 10 days. All data obtained from n = 6 mentioned two different samples were presented as log CFU/g in the present study.

2.2.8. Statistical analysis

All data obtained from TMABc, TPBc, *E. coli*, and *Salmonella typhimurium* analysis results were performed by using analysis of variance (ANOVA) with the SPSS (2008) computer program, and the level of significance was determined as $p < 0.05$. The Dunnett test was used to reveal the statistical significance between the monitored variances.

3. Result and Discussion

3.1. Morphological characterization of garlic shell nanofibers

SEM images of the produced nanofibers are shown in Fig. 3 via different magnifications (200 nm, 500nm, and 2000 nm) and Fig. 2, respectively. The SEM images reflected that the nanofibers fabricated via garlic shell were effectively obtained. In this regard, the average diameters of the fabricated nanofibers were determined between 23.567 and 431.170 nm, while the mean value was 71.869 ± 52.830 nm. As the nanofibers' diameters indicated, integration of garlic shell into PVA raised the diameter of the fabricated nanofibers. The other published studies related to nanofibers noted that the combination of materials into the wall material could raise the diameter of nanomaterials (Yaman et al., 2022; Sriyanti et al., 2024). Furthermore, the type of materials (polysaccharide or protein etc.), the parameters of electrospinning such as applied voltage, distance between collector and Taylor cone and also collector type so on can play a key role for successfully fabrication as stated by Hosseini et al., (2019), Ceylan et al., (2023), and Zhou et al., (2023). One of the main targets of the present study was to

eliminate pathogenic microorganism growth; thus, the application of the fabricated nanofiber with 71.869 nm might have limited the rapid growth of microorganisms by presenting a larger contact area on the surface of the bacteria, which was responsible for the spoilage of red meat samples stored at 4°C.

3.2. Thermal characterization of fabricated garlic shell nanofibers

Two different slopes defined with green one: TGA and purple one: dTG were obtained to determine the mass loss in the fabricated nanofibers (Fig. 4). In this respect, the mass loss depending on temperature was defined here. Two crucial temperatures, such as at 278°C and 513°C, while the total mass loss was defined as 86.093%. Moreover, the temperature between 25–250°C showed a slower mass loss that might be related to moisture and evaporation of low-molecular components. Especially at 280°C, a certain loss in the mass of the fabricated nanofibers was detected. Because of a sudden loss in mass, it is defined that the nano-scale material consists of organic material. When the results are especially evaluated in the scope of the present study, red meat samples are mostly cooked around 200°C or marinated or stored under lower temperatures; thus, mass loss was not significantly detected at the mentioned temperature. When the other studies based on nanobiotechnology integrated with food were evaluated, it was seen that the nanofiber fabricated with biopolymer had a thermal decomposition with 11.8 and 10.77% at a lower temperature than 150°C, as stated by Ceylan et al. (2017). The nanofibers obtained from zein did not undergo thermal decomposition. On the other hand, thermal decomposition resulting with weight loss at 60 and 150°C (up to 4%) was detected because of the fact that water evaporation was observed. Moreover, the main thermal decomposition was determined around 300°C, which could be integrated with the thermal decomposition of the polymer structures according to Erdoğan et al. (2015) and Moreno et al. (2019). As a conclusion related to TGA, thermal behaviours of fabricated nano-scale material are crucial, especially for the cooking temperatures of red meat samples.

3.3. FTIR evaluation of garlic shell nanofibers

Figure 5 presents an FTIR (Fourier Transform Infrared) spectrum plotted as percent transmittance versus wavenumber in the range of approximately 4000–500 cm^{-1}. Overall, the spectrum showed several well-defined absorption bands, indicating the presence of multiple functional groups and a chemically complex structure. The broad and intense absorption observed in the high-wavenumber region around ~ 3300–3400 cm^{-1} is characteristic of O–H stretching vibrations. The breadth of this band suggests hydrogen bonding, which is commonly associated with hydroxyl groups in alcohols, phenols, or adsorbed moisture. This feature implies the presence of polar functional groups that can engage in intermolecular interactions. In the region near ~ 2920–2850 cm^{-1}, weaker but noticeable absorption bands were present, which could be attributed to C–H stretching vibrations of aliphatic $–CH_2$ and $–CH_3$ groups (Deepika et al., 2021 and Truzzi et al., 2021). These peaks indicated the presence of saturated hydrocarbon chains or alkyl substituents within the structure. The moderate intensity of these bands suggests that aliphatic components were present but were not the dominant feature of the material. A

prominent and sharp absorption band appeared around ~ 1730–1750 cm^{-1}, which was typically assigned to C = O stretching vibrations. This strong peak was indicative of carbonyl-containing functional groups such as esters, carboxylic acids, aldehydes, or ketones. The sharpness and depth of this band imply a significant concentration of carbonyl groups, which often could have played a key role in determining the chemical reactivity and physical properties of the material. In the fingerprint region (1500–500 cm^{-1}), multiple intense and closely spaced absorption bands were also observed. Peaks around ~ 1450–1380 cm^{-1} were commonly associated with bending vibrations of C–H bonds, while absorptions near ~ 1250–1050 cm^{-1} might be assigned to C–O stretching vibrations. Moreover, 1365 and 1645 cm^{-1} could be assigned with antimicrobial and medicinal properties from active sulphur compounds, like allicin, as stated by Lu et al. (2011). These features further supported the presence of oxygen-containing functional groups, such as esters or ethers. Strong bands below 1000 cm^{-1} might correspond to out-of-plane bending vibrations or skeletal vibrations of the molecular backbone, which were highly specific to the compound's structure. Moreover, the FTIR spectrum revealed the coexistence of hydroxyl, aliphatic, carbonyl, and C–O functional groups. The combination of a broad O–H band, a strong carbonyl absorption, and multiple fingerprint-region peaks suggested a multifunctional organic material with significant polarity and structural complexity. These spectral characteristics provided valuable insight into the chemical composition and could be used to support material identification, confirm functionalization, or compare structural changes in related samples. All these results given above reflected a successful fabrication of nanofibers.

3.4. Garlic shell nanofibers *on Salmonella typhimurium*

During the initial storage period, the values of both groups were very close to each other (control samples: 2.62 log CFU/g and meat samples treated with nanofiber: 2.64 log CFU/g). The result given in Table 1 indicated that the experiment started under similar initial conditions. Meat samples treated with nanofiber showed consistently lower *Salmonella typhimurium* levels as compared with the control group from day three onwards. The difference based on log CFU/g exceeded 0.65, particularly between the third and 9th days. By the end of day 11, the red meat samples treated with the nanofiber group (2.73 log CFU/g) showed a more successful reduction than the control group's level on day 11 (3.09 log CFU/g), almost returning to the initial day level. Moreover, the nanofiber application with red meat samples stored at 4°C was more successful in suppressing *Salmonella typhimurium* growth compared with the Control group red meat samples. In the control group, the *Salmonella typhimurium* bacterial population reached higher levels and showed a slower decline as compared to the red meat samples treated with nanofibers fabricated in the present study ($p < 0.05$). Nano-based materials can provide a larger surface area on the surface of the material attached. Recently published study results revealed that some pathogenic microorganism growth could be effectively declined. In this respect, thyme oil nanoemulsions with 219 nm and 163 nm diameters provided a key role in the inhibition of *Salmonella typhimurium* as stated by Meral et al. (2019). Understanding the fabrication of novel materials might be a critical issue; in this sense, according to Memar et al. (2017), permeabilization, depolarization, and disruption of the cytoplasmic membrane play a key role in determining the antibacterial properties of the

compounds. Entezari et al. (2023) noted that gelatin-pullulan-nanofibers cellulose film decreased *Salmonella typhimurium* (non-food treatment) by up to 1 log than control samples at 4°C during 9 days of storage. As could be seen from the results of the present study, the novel treatment or substance used had a clear inhibitory effect on *Salmonella typhimurium* growth in red meat samples stored at cold storage conditions.

Table 1
Salmonella growth depending on nanofiber treatment and storage days (n = 3).

Storage Days	Control (log CFU/g)	Nanofiber (log CFU/g)
1	2.62 ± 0.028^{a}	2.645 ± 0.007^{a}
3	4.49 ± 0.042^{b}	3.84 ± 0.028^{a}
5	4.24 ± 0.028^{b}	3.76 ± 0.056^{a}
7	3.81 ± 0.014^{b}	3.49 ± 0.014^{a}
9	3.52 ± 0.028^{b}	2.86 ± 0.028^{a}
11	3.095 ± 0.035^{b}	2.73 ± 0.056^{a}

3.5. Garlic shell nanofibers *on E. coli*

The results of the *E. coli* analysis (Table 2) on red meat samples treated with nanofibers reflected a clear and significant antimicrobial effect compared to the control group samples stored at 4°C. In other words, the fabricated nanofiber treatment consistently maintained lower *E. coli* counts throughout the 11-day storage period. Right from the first day, there was a notable difference. The nanofiber sample started at 4.49 log CFU/g while the control was at 4.96 log CFU/g, indicating an immediate inhibitory effect of the nanofibers, and then between days 3 and 5, the gap between the control and the nanofiber samples narrowed slightly. This suggested a period where the bacterial growth or survival was relatively similar, although the *E. coli* load of the nanofiber red meat sample remained lower. So, this period for the nanofiber treatment was able to be called the stabilization period. From day 7 onwards, the effectiveness of the nanofibers significantly increased again. While the control group's count fluctuated between 4.25 and 4.50 log CFU/g, the treated nanofiber sample continued to decline, reaching its lowest point of 3.615 log CFU/g by the end of the study. In this regard, the nanofiber treatment reached its maximum effectiveness on day 11, achieving a log reduction of 0.885, which corresponded to a 20% reduction in the *E. coli* population compared to the control red meat samples ($p < 0.05$). Novel approaches like biosensors fabricated by electrospun cellulose acetate nanofibers (Zhang et al., 2024), besides conventional methods, are gaining much more importance to inhibit *E. coli* presence in food. In this respect, Soltaninezhad et al. (2020) reported that with the use of chitosan/cellulose nanocombination, *E. coli* count was significantly decreased in the range of 0.2 and 1.2 log CFU/g in the nano treatment

groups as compared to the (non-nano treatment) control group in the hamburger samples stored at 4°C for 12 days.

Table 2
E. coli counts depending on nanofiber treatment and storage days (n = 3).

Storage Days	Control (log CFU/g)	Nanofiber (log CFU/g)
1	4.96 ± 0.03^{b}	4.49 ± 0.01^{a}
3	4.83 ± 0.01^{a}	4.61 ± 0.01^{a}
5	4.78 ± 0.04^{b}	4.54 ± 0.03^{a}
7	4.79 ± 0.02^{b}	4.16 ± 0.08^{a}
9	4.25 ± 0.07^{b}	3.76 ± 0.11^{a}
11	4.50 ± 0.03^{b}	3.62 ± 0.02^{a}

3.6. Garlic shell nanofibers on the total mesophilic bacteria count of red meat

The results related to the total mesophilic bacteria count (TMABc) are given in Fig. 1. As can be seen from the figure, the initial load (day 1), the nanotreated red meat samples started with a lower bacterial count (4.395 log CFU/g) as compared to the control (4.750 log CFU/g), indicating an immediate inhibitory effect. Initial load can reflect poor sanitary conditions during slaughter or subsequent processing factors (Gill et al., 1998; Ghafır et al., 2008; Nakamura et al., 2023). Furthermore, $<10^5$ CFU/g is used to determine good hygiene and cold chain management, while 10^5-10^6 CFU/g determines approaching shelf-life limit values (Nakamura et al., 2022). As storage progressed, the bacterial population in the control group grew rapidly, reaching 5.740 log CFU/g by day 3. In contrast, the nanofiber treatment significantly slowed this growth, maintaining the count at 5.200 log CFU/g (reduction: 0.54 log CFU/g; approx.. %10) ($p < 0.05$). Electrospun eugenol and gelation combination in nanofiber as bioactive packaging limited the TAMBc up to 1.62 log CFU/g in beef samples (Yılmaz et al., 2022). In addition to the study recently published, Ceylan et al. (2023) noted that nanofibers fabricated with sesame oil retarded TAMB growth up to 18% in chicken meat samples stored at 4°C. By the end of the 11-day study, the Control group reached a peak of 6.125 log CFU/g. Generally, a TAMB count exceeding 6.0 log CFU/g is considered the threshold for the beginning of spoilage in many regulatory contexts. While the Control group crossed this threshold by day 11, the Nanofiber-treated re meat sample remained below it, 5.850 log CFU/g, demonstrating the treatment's ability to keep the product within acceptable microbial limits for a longer duration. Above all, material type and the diameter of fabricated material might play a key role in limiting the rapid TAMB in red meat samples stored at 4°C.

3.7. Garlic shell nanofibers on the total psychrophilic bacteria count of red meat

Figure 2 summarized the findings from the psychrophilic bacteria growth (TPBc) of red meat samples stored for 11 days, comparing a control (non-nanotreatment) group with samples treated with a specialized nanofiber application for red meat samples. TPBc's ability to grow at low temperatures may limit the shelf life of red meat, leading to economic losses and potential food safety concerns. TPB may be a useful predictor for the hygienic condition of meats at low temperature and their spoilage potential. In addition to this, Psychotropic bacteria were prevalent in all red meat samples up to 6.2 log CFU/g for local and imported samples (Al-Mazrouei et al., 2024). So, besides or instead of conventional methods, novel methods like nanotechnology-based applications are receiving a great deal of attention to delay TPBc growth in the food industry. On the first day of the analysis period, two groups started with similar microbial loads ~ 2.9 log CFU/g, indicating a consistent baseline ($p > 0.05$). On the other hand, the control samples exhibited rapid bacterial growth, increasing by 3.41 log CFU/g units over 11 days, reaching 6.30 log CFU/g. On the contrary, the nanofiber-treated red meat samples indicated a much slower growth rate. By Day 11, the count was only 5.10 log CFU/g, an increase of 2.15 log CFU/g. There was a statistical difference between the two groups ($p < 0.05$). Jafarinia et al. (2022) noted that nanoemulsions (181 nm) treated with lamb loins provided lower TPBc in the range of 1.22 and 2.54 log CFU/g as compared to control samples, whereas the initial load was detected between 2.87–3.26 log CFU/g, and a statistical difference was not detected at 0 and 4 days. Also, 121 nm nanoemulsions obtained from cumin and safflower treated with lamb meat delayed TPBc growth stored samples for 12 days as stated by Hasani-Javanmardi et al. (2021). McClements et al. (2021) also reviewed that nanoscale materials could retard rapid TPBc growth in different food samples, such as chicken, turkey, fish fillets, besides apple, cheese, and cabbage. In the present study, the nanofiber treatment for red meat samples effectively suppressed the growth of psychrophilic bacteria over the 11-day cold storage period. The significant reduction in TPB load, particularly after one week of storage, suggested that this treatment could substantially prolong the shelf life of refrigerated red meat.

4. Conclusion

The present study demonstrated that the fabrication of nanofibers via garlic shell was successfully applied through an electrospinning procedure. FTIR analysis results validated the presence of bioactive functional groups, including sulphur compounds like allicin. TGA results indicated that the material remains thermally stable at common meat processing temperatures, losing significant mass only beyond 280°C. Furthermore, the fabricated nanofibers played a key role in antimicrobial efficacy. In this respect, microbiological assessments proved that this nano-scale material effectively enhanced food safety during cold storage at 4°C. The treatment significantly suppressed the growth of *Salmonella typhimurium* and *E. coli*, achieving notable log reductions compared to control groups, besides the nanofibers effectively retarded the proliferation of total mesophilic and psychrophilic bacteria, keeping the red meat samples below the established spoilage threshold for a longer duration. These results

highlighted the potential of garlic-based nanofibers as an innovative, bio-based packaging solution for the food industry, especially red meat samples, offering a sustainable approach to extending shelf-life and ensuring human health.

Declarations

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This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

The datasets analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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Figures

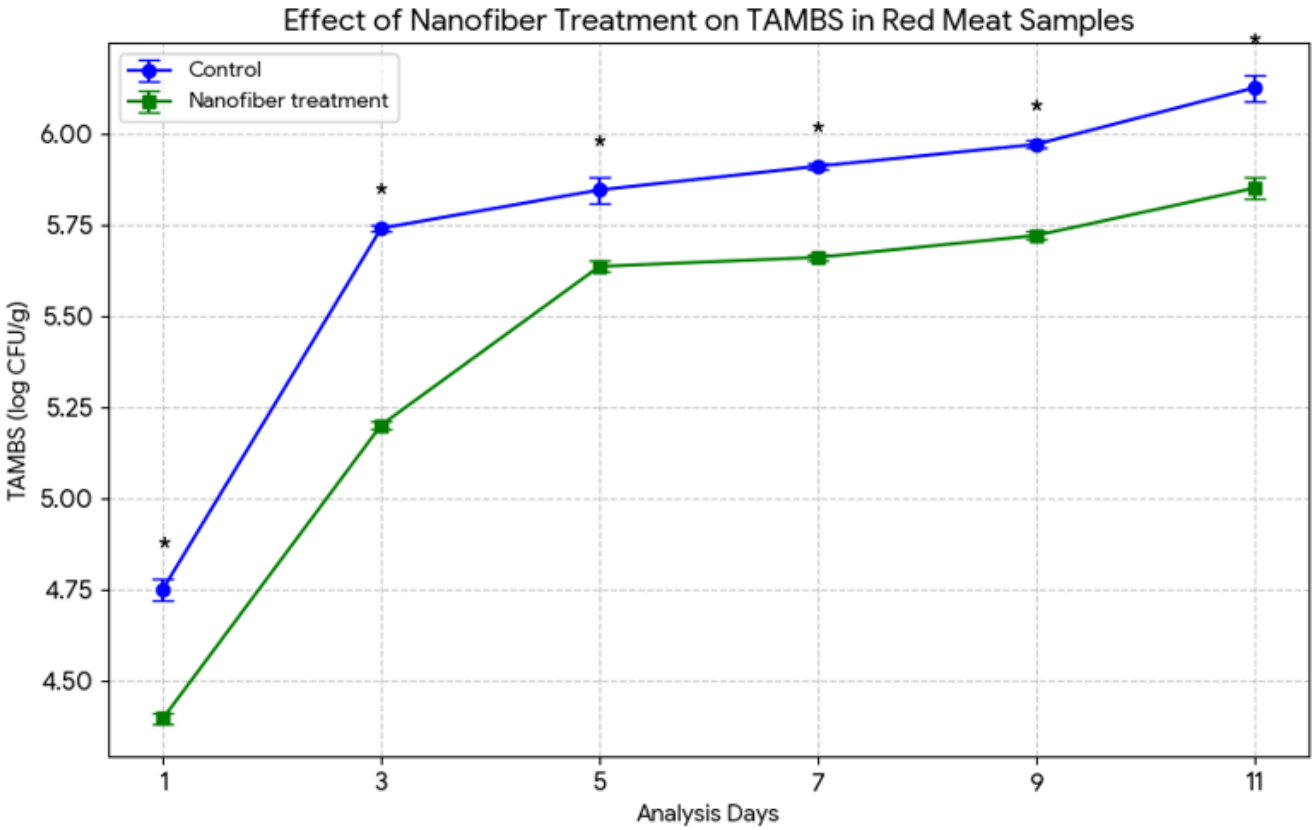


Figure 1

The effect of nanofiber treatment on TAMB growth in red meat.

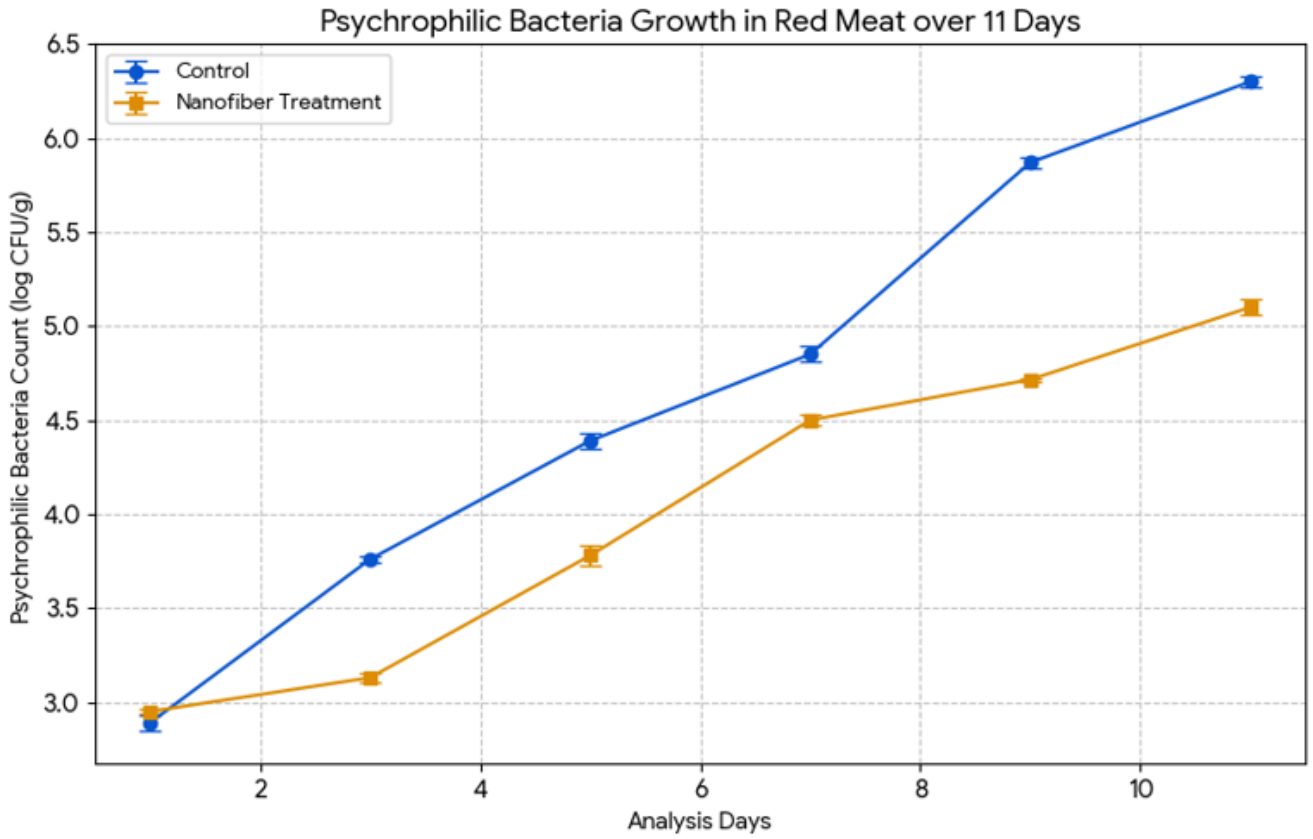


Figure 2

The effect of nanofiber treatment on TPB growth in red meat.

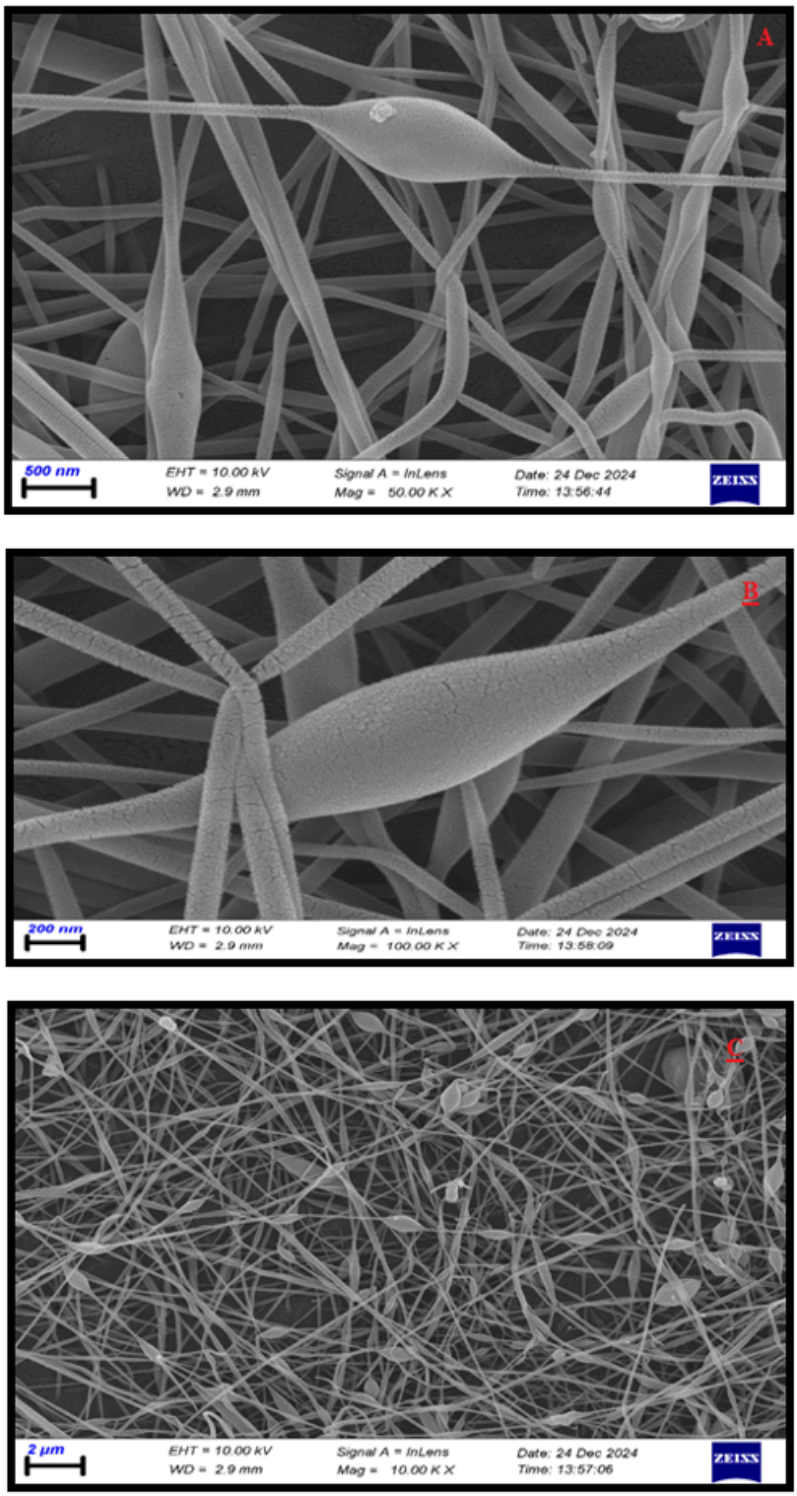


Figure 3

SEM İmages of Fabricated nanofibers with 50.00 KX (A), 100.00 KX (B), and 10.00 KX (C)

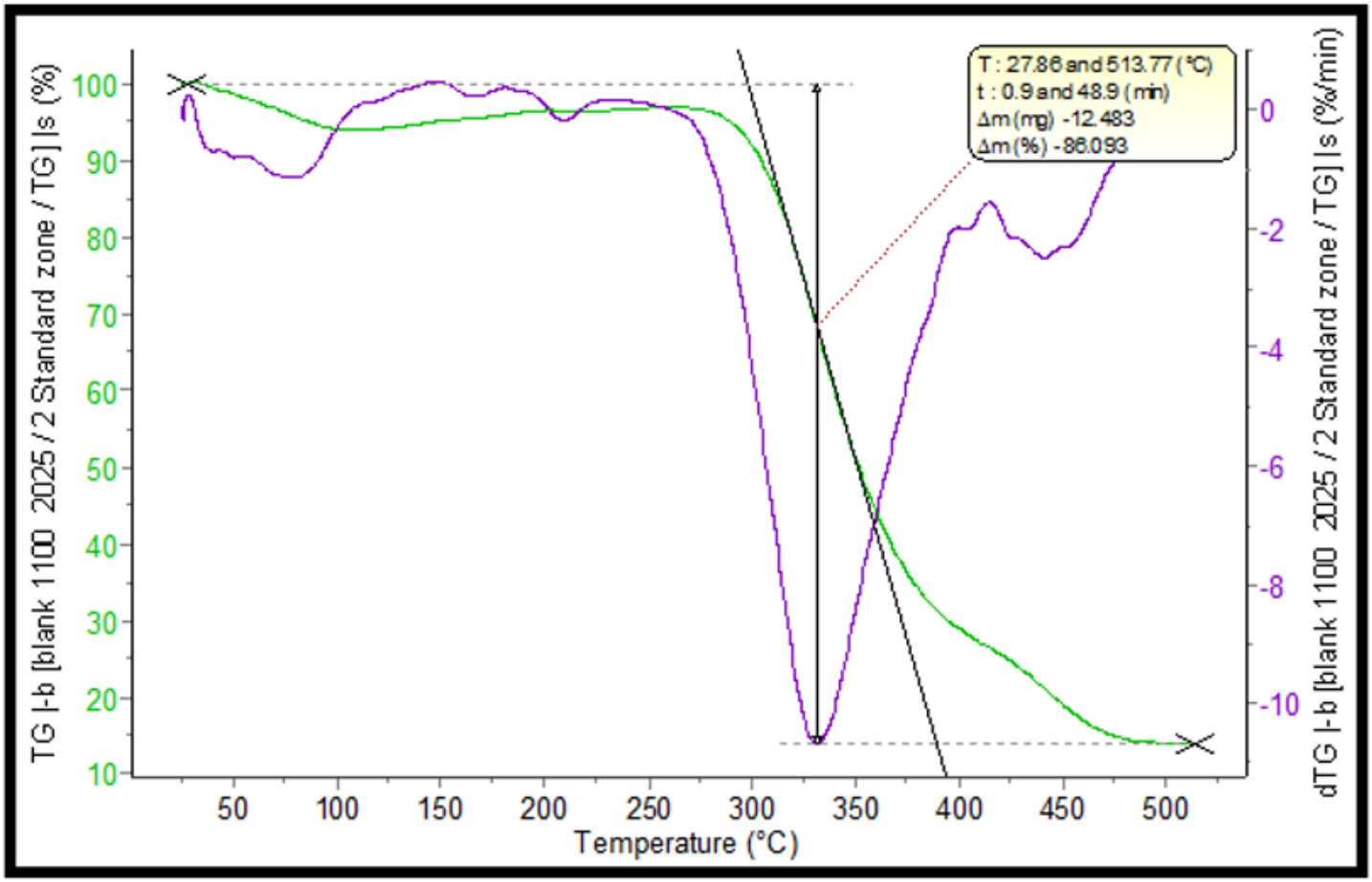


Figure 4

TGA results of the fabricated nanofibers.

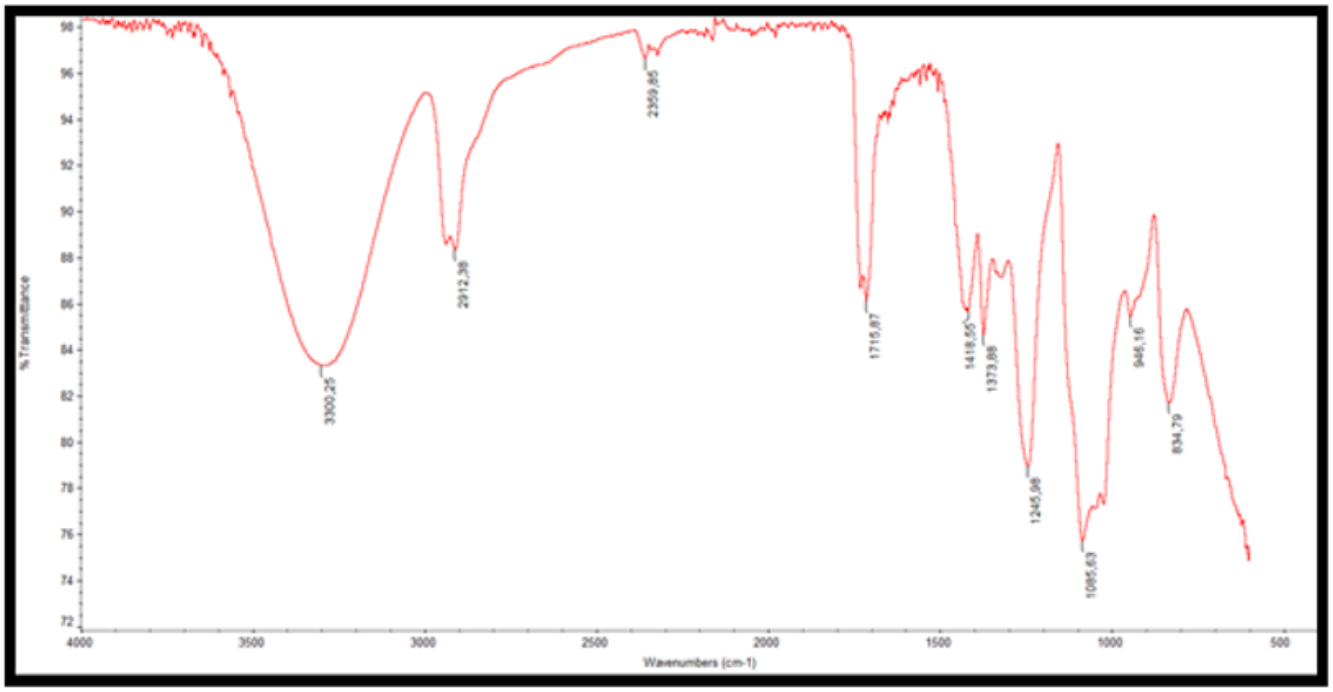


Figure 5

FTIR perspective of the fabricated nanofibers.

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