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Original article

Electro-blown micro-nanofibrous mats with *Origanum elongatum* essential oil for enhancing the shelf life of tomato (*Solanum lycopersicum*)

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Summary This study aims to develop a novel active food packaging material from hybrid micro-nanofibrous mats fabricated from gelatin (G)–chitosan (Ch)–polyvinyl alcohol (PVA)–*Origanum elongatum* essential oil (EO), (G-Ch-PVA-EO) through electro-blowing. The fibrous mats were characterised to assess their morphologies, shelf life efficiency, antimicrobial and antioxidant properties, surface-wetting, and thermal, chemical, and physical interactions, among other factors. Results showed that the antioxidant activity was improved with the addition of EO, this enhancement is potentially linked to its rich content of phenolic components; carvacrol and P-cymene. In addition, G-Ch-PVA-EO showed higher firmness measurements compared to the control samples. Herein, low microbial counts were noted for both mesophilic aerobic bacteria (3.76 log CFU g^{-1}) and yeast/mould (3.91 log CFU g^{-1}) even at day 20. To conclude, the G-Ch-PVA-EO microfibrous mat exhibits great promise in preserving the freshness of tomatoes.

Keywords Chitosan, gelatin, *Origanum elongatum*, polyvinyl alcohol.

Introduction

The anticipated rise in the global population to 8.5 billion by 2030 and 9.7 billion by 2050 will lead to a significant increase in food demand, as fresh fruits and vegetables are lost during post-harvest handling and storage driving the need for new food packaging materials. However, traditional packaging materials have environmental drawbacks (Ncube *et al.*, 2021). Despite 9.9% of the world still experiencing famine, 1.3 billion tons of food are wasted annually (Ullah *et al.*, 2023). This highlights the need for innovative, eco-friendly packaging solutions to reduce waste by extending the shelf life of food products (Petkoska *et al.*, 2021).

Biodegradable materials such as cellulose (Hai *et al.*, 2020), starch (Fonseca *et al.*, 2019), chitosan (Tien *et al.*, 2021), and gelatin (Doğan *et al.*, 2022b) have been investigated for their potential applications in the production of fibrous mats for food packaging. Gelatin, a biopolymer known for its safety and affordability, is being studied for food packaging (Lu *et al.*, 2022). However, it has weaknesses in mechanical strength and water vapour permeability (Zhang *et al.*, 2010). The low elongation of gelatin nanofibers is likely due to their short polymer chains. This also leads to a shorter food shelf life compared to conventional packaging materials (Haghighi *et al.*, 2021). To overcome these limitations and expand its potential use in food packaging and future commercialisation, gelatin will be thermally crosslinked and or combined with polysaccharides (Rhim *et al.*, 2013; Ehrmann, 2021) or other biodegradable polymers such as polyvinyl alcohol (PVA) (Chi *et al.*, 2022).

Chitosan is another biodegradable polysaccharide derived from chitin by partial deacetylated (Gulzar

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et al., 2022). Past research studies showed that the characteristics of gelatin nanofibrous mats were remarkably enhanced by blending them with chitosan (Duan *et al*., 2023). The tensile strength of the chitosan-gelatin blend nanofibers was 19.07% higher than the neat gelatin (Yang *et al*., 2007). On the other hand, PVA is a synthetic, water-soluble, and non-toxic polymer that was evaluated for safety by the Joint World Health Organization (WHO) Expert Committee on Food Additives (JECFA) in 2003 (WHO, 2004) and was also approved by the United States Department of Agriculture (USDA) for packaging meat and poultry products (Haghighi *et al*., 2021). PVA is biodegradable with high elongation, gas barrier properties, and flexibility. PVA and gelatin are highly miscible and compatible due to PVA's multifunctional polymer backbone. Studies have shown that incorporating PVA into gelatin solutions, ranging from 10 to 70 wt.% significantly enhances the tensile strength from 2.4 to 8.6 MPa and the elongation at the break from 4 to 25% in gelatin/PVA nanofibers (Yang *et al*., 2007). Another study by Merkle *et al*. (2013) demonstrated that core-shell structured PVA-gelatin nanofibers exhibit improved Young's modulus and tensile strength. The addition of PVA considerably improves the mechanical properties of gelatin, increasing its Young's modulus and ultimate tensile strength from 21.52 ± 4.15 to 168.6 ± 36.5 MPa and from 0.48 ± 0.02 to 5.42 ± 1.95 MPa, respectively (Merkle *et al*., 2013).

ES is a popular low-cost method for producing submicron and nano-metric fibres from various polymers (Han *et al*., 2020). However, this technique has some limitations related to the high voltage required and the low production rate (Stojanovska *et al*., 2016; Akhouy *et al*., 2023; Kilic *et al*., 2023). Alternatively, solution blow spinning (SBS) is another method for producing fibres with micro and nano-scales (Dadol *et al*., 2020). Electro-blowing is a hybrid nanofiber manufacturing technique that combines the benefits of both SBS and ES (Eticha *et al*., 2023).

Active food packaging often involves embedding antimicrobial and antioxidant bioactive compounds within polymer-based nanofibers (Dayisoylu *et al*., 2023; C. Doğan *et al*., 2022a). Many plant extracts, essential oils, and derivatives have been studied for potential applications in active food packaging because of their antimicrobial and antioxidant properties (Arruda *et al*., 2022). As one of the essential oil sources, *Origanum elongatum* (OE), an endemic, aromatic medicinal herb found primarily in Morocco, is rich in essential oils. Scientific studies have demonstrated that the essential oil of OE possesses antimicrobial, antioxidant, and insecticidal properties (Tagnaout *et al*., 2023; Drioiche *et al*., 2024). The composition of the essential oil (EO) obtained from the flower heads of OE through hydrodistillation has been examined, revealing constituents such as Carvacrol, Thymol, and Pinene, which provide both antioxidant and antibacterial properties (Ramzi *et al*., 2017).

This study focused on developing novel food packaging micro-nanofibrous mats from gelatin-chitosan-polyvinyl alcohol using the innovative electro-blowing technique. Herein, crosslinked samples underwent characterisation including morphologies, surface wetting, air permeability, thermal properties, physical and/or chemical interactions, and many more. Additionally, for the first time, the antibacterial and antioxidant activities of the hybrid micro-nanofibrous mats containing *Origanum elongatum* essential oil (EO) were investigated. Herein, by utilising EO-loaded micro-nanofiber materials, this study also investigates the characteristic response of the micro-nanofiber's packaging material's ability to inhibit bacterial growth and oxidative reactions, thereby extending the shelf life of packaged food products.

Materials and methods

Materials

Ch (Deacetylation degree >95%) was purchased from Biyopol (Istanbul, Türkiye). PVA (0.4–0.6 g cm^{-3}, purity 87.8%) supplied from ZAG Kimya (Istanbul, Türkiye). G (Bloom 250–270, Type B) produced from bovine skin was supplied in powder form from Halavet Gida LLC (Istanbul, Türkiye). Acetic acid (AA) (80% purity, 1.08 $g.cm^{-3}$) from Tekkim (Bursa, Türkiye).

Isolation of essential oil (EO)

To extract EO, the Clevenger apparatus, a widely used method for extracting essential oils from plant materials via hydro-distillation, was used. This method is cost-effective and environmentally friendly because of not use any organic solvents. The flowered tops and leaves of the OE plant are extracted for 4 h. The extracted EO was dried over anhydrous sodium sulfate and stored at 4 °C in the dark until required.

Fabrication methods

Preparation of solutions

Four solutions were prepared to address specific aspects of the research objectives as follows. For the first solution, 16 wt.% of gelatin powder was dissolved in acetic acid/distilled water (90/10 wt.% ratio), at 60 °C and magnetically stirred for 6 h. The second solution, a blend of G and Ch, was prepared by dissolving 11 wt.% of G in acetic acid/distilled water (90/10 wt.% ratio), at 60 °C and magnetically stirred for 3 h. Then, 5 wt.% of Ch was added and stirred for 6 h. The third solution was prepared by dissolving G, Ch, and PVA in a weight ratio of 2:1:1. For this,

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firstly, G was dissolved in acetic acid/distilled water (90/10 wt.% ratio), at 60 °C and stirred for 3 h. Simultaneously, the PVA solution was prepared by dissolving PVA in ethanol/water (60/40 wt.% ratio) at 80 °C and stirring for 4 h. Following, G and PVA solution were mixed, and then Ch was added, and the solution was stirred at 80 °C for another 8 h to obtain a homogenous solution. The last solution, G/Ch/PVA/EO solution was prepared by mixing EO of 5 wt.% of the total weight of the polymer with G/Ch/PVA solution and stirred for an additional 1 h.

Production of micro-nanofibrous mats

The electro-blowing method was used to produce micro-nanofibrous mats. As shown in Fig. 1, 1 bar-pressured air provided by a compressor was used to spin the solution, which is pumped by a syringe pump through a nozzle needle at a flow rate of 15 mL/h. In addition, to improve solution spinnability, a DC electrical voltage of 10 kV was applied to the nozzle. Finally, the fibres were collected over a rotating collector 45 cm away from the nozzle tip onto a spun-bond polypropylene nonwoven substrate. Afterward, the produced micro-nanofibrous mats were thermally crosslinked in a Protherm furnace at 140 °C.

Characterisation of fibrous mats

Detailed information regarding characterisations is available in the Appendix S1.

Packaging test of micro-nanofibers

To assess the effectiveness of the prepared micro-nanofibrous mats in enhancing the shelf life of red cherry tomatoes, a controlled experiment was conducted. Fresh red cherry tomatoes of uniform size, shape, and colour, with no visible defects or bruises, were selected for the study. These tomatoes were initially washed thoroughly under running tap water to remove any surface contaminants. Following this, they were sterilised by immersing them in a sodium hypochlorite solution for a few minutes to ensure the elimination of microbial contaminants. After sterilisation, the tomatoes were carefully air-dried at room temperature. The prepared micro-nanofibrous mats were then individually wrapped around each tomato, ensuring full coverage and secure adhesion. The mats were affixed using a small amount of tape to prevent slippage and to maintain the integrity of the wrapping throughout the storage period. This served as the experimental group. For the control group, a conventional plastic (polyethylene) cling film was used to wrap an equivalent set of tomatoes, replicating the same wrapping procedure. The wrapped tomatoes from both groups were stored on an open laboratory shelf at ambient conditions (approximately 25 ± 4 °C), mimicking typical storage environments. The tomatoes were monitored over a 20-day period, with evaluations conducted at 5-day intervals. During each evaluation, several key parameters were assessed, including visual appearance, weight loss, firmness, pH levels, and microbial load. The detailed methodologies for measuring these parameters are provided in the Appendix S1.

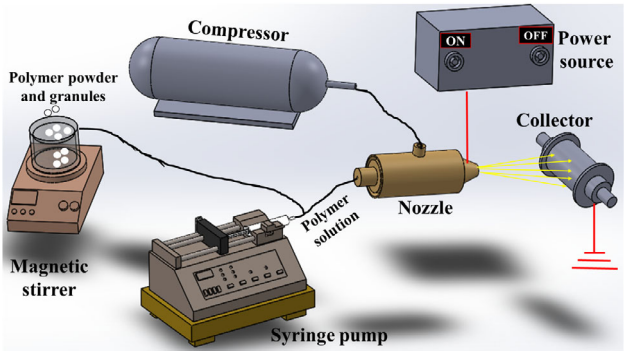


Figure 1 Schematic diagram of Electro-blowing.

Results and discussion

Identification of EO composition

The strong antibacterial and antioxidant activities of the essential oils are primarily attributed to their chemical composition, particularly the presence of monoterpene hydrocarbons, oxygenated monoterpenes, and sesquiterpenes (Bhavaniramya *et al.*, 2019). The result of GC–MS of EO is presented in Table 1. Accordingly, among the compounds detected is carvacrol, which represents the majority component with a percentage of 55.32%, followed by P-cymene, γ-terpinene, linalool, and thymol with a percentage of 14.7%, 9.84%, 2.94%, and 2.71% of the total composition, respectively.

This antibacterial and antioxidant activity is attributed to the presence of high-concentration components, such as carvacrol, as well as synergistic interactions between major and minor components (Oualili *et al.*, 2019). Carvacrol has been previously utilised by Fonseca *et al.* (2019), who developed an antimicrobial and antioxidant electrospun soluble potato starch nanofibers loaded with carvacrol. It was reported that the antioxidant activity of the nanofibers increased with the carvacrol concentration, up to 83% with nanofiber loaded with 40% (v/v) of carvacrol. Electrospun nonwovens with 30% (v/v) of carvacrol reduced the growth of *L. monocytogenes*, *S. typhimurium*, *E. coli*, and

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Table 1 Composition of *Origanum elongatum* EO

No	Component	RI	%
1	α-Thujene	930	0.23
2	α-Pinene	939	0.75
3	Camphene	954	0.12
4	Octen-3-ol	979	0.61
5	β-Pinene	979	0.09
6	Myrcene	990	1.43
7	α-Phellandrene	1009	0.19
8	α-Terpinene	1017	1.1
9	*p-Cymene*	1024	14.7
10	Limonene	1029	0.37
11	1.8-Cineole	1031	0.31
12	γ-Terpinene	1059	9.84
13	cis-4-thujanol	1070	0.04
14	Terpinolene	1088	0.12
15	*p*-cymenene	1091	0.12
16	Linalool	1096	2.94
17	Terpinen-4-ol	1177	0.28
18	α-Terpineol	1188	0.4
19	Tymol, methyl ether	1235	0.18
20	Thymol	1290	2.71
21	Carvacrol	1299	55.32
22	Caryophyllene <(Z)>	1412	2.38
23	α-Humulene	1500	2.3
24	α-Muurolen	1500	0.18
25	γ-Cadinene	1523	0.22
26	Thymohydroquinone	1555	0.29
27	Caryophylleneoxide	1583	2.01
	Total identified compounds		99.23

RI, Retention Index.

S. aureus, by 89, 68, 62, and 49, respectively. In addition, the electrospun nonwovens maintained their antibacterial activity against, *S. aureus* for up to 30 days. Therefore, the components found in *Origanum elongatum* essential oil exhibited great antioxidant and antimicrobial activities, which may be useful in applications such as active food packaging systems to extend the shelf life and ensure the safety of food products.

SEM morphologies of hybrid micro-nanofibers

The morphologies of G, G-Ch, G-Ch-PVA, and G-Ch-PVA-EO micro-nanofibrous mats were examined through SEM, and the SEM images and diameter distribution of samples are depicted in Fig. 2. A droplet and bead-free fibrous structure with homogenously distributed fibres were noted for all samples. The neat G sample has relatively thin nanofibers with a mean diameter of 210.77 ± 3.32 nm. The average diameters of the nanofibers for the G-Ch sample (578.20 ± 21.91 nm) experienced a growth of over two-fold in contrast to neat G. This increase can be linked to the rise in solution viscosity attributed to the addition of Ch. The incorporation of a 25% mass fraction of PVA into G-Ch resulted in a further increment of average fibre diameter from 578.20 ± 21.91 to 1266.32 ± 61.34 nm. This was also because of the same reason stated above. The same results were corroborated by Yang *et al.* (2007), who also observed that an increase in the PVA ratio led to a rise in the viscosity of the G solution. This increase in viscosity corresponded with an increment in fibre diameters. Furthermore, the fibre diameter of the G-Ch-PVA sample increased with 5 wt.% EO incorporation to 1300 ± 15.40 nm. The addition of EO to the G-Ch-PVA solution suggests increased viscoelastic forces, thereby neutralising the driving force of the airflow and preventing the polymer jet from stretching, resulting in thicker microfibers with larger fibre diameter (Mendes *et al.*, 2023). Similar findings were noticed by Vafania *et al.* (2019), the addition of thyme essential oil addition into a chitosan-gelatin solution resulted in an increment in fibre diameter. This might be due to decreased electrical conductivity, which reduced the elongation of the polymer jet by the applied voltage, increasing fibre diameter.

Regarding the fibre diameter distribution, neat G has a narrow distribution ranging from 100 to 500 nm. The addition of Ch to the G solution appears to have a wide impact on the distribution of fibre diameters, resulting in a range of 200 to 1400 nm. With the addition of PVA to the blend solution, the fibre diameter has shifted from the nano to the microscale, covering a distribution range of 500 to 2500 nm.

Mechanical properties

The mechanical properties of micro-nanofibrous samples were investigated to ensure their sustainability for long-term use. The tensile strength (TS) and elongation at break (EAB) values are presented in Table 2. Notably, the G-Ch-PVA sample exhibited the highest tensile strength of 1.3672 ± 0.226 MPa. This significant result is attributed to the strategic incorporation of PVA into the polymer matrix, a phenomenon corroborated by Yang *et al.* (2007). Their study similarly highlighted the positive impact of adding PVA to a gelatin solution, showcasing an increase in tensile strength from 2.4 to 8.6 MPa. Conversely, the incorporation of EO led to a noticeable decrease in tensile strength. Building on the findings of Wang *et al.* (2021), the effect of essential oils varied depending on the specific interactions between the oil components and the polymer matrix (Bonilla *et al.*, 2018). The following mechanisms are proposed: (1) Essential oils can reduce tensile strength by lowering cohesion forces within polymers. Strong interactions between chitosan and gelatin are partially

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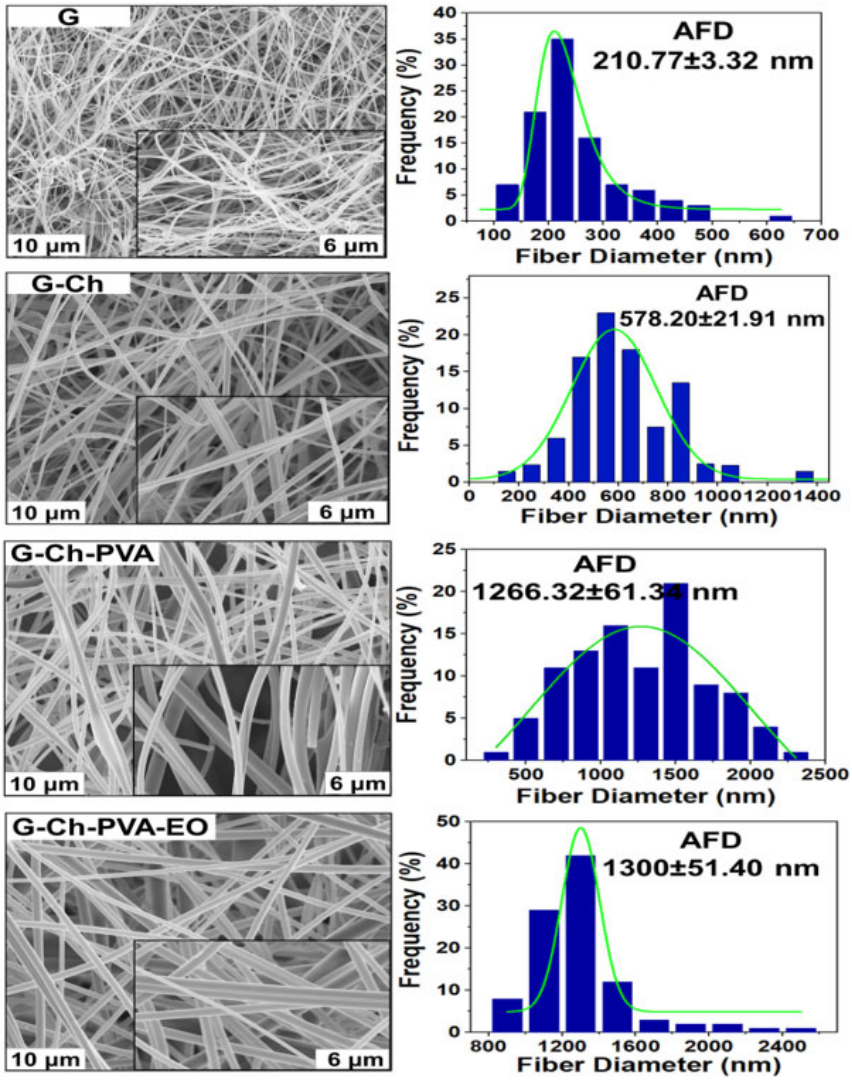


Figure 2 SEM micrographs of micro-nanofibrous mats and their AFD distributions.

Table 2 Mechanical properties of micro-nanofibrous mats

Sample code	Tensile strength (MPa)	Elongation at break (%)
G	0.8345 ± 0.322	6.63 ± 2.322
G-Ch	0.9781 ± 0.265	8.16 ± 2.528
G-Ch-PVA	1.3672 ± 0.226	6.63 ± 1.988
G-Ch-PVA-EO	1.2374 ± 0.248	7.47 ± 2.114

replaced by weaker polymer-oil interactions; (2) Essential oils, being hydrophobic compounds, may cause a heterogeneous film network and discontinuous microstructure through biopolymer rearrangement, resulting in decreased mechanical performance (Haghighi *et al.*, 2019).

Antioxidant activity

Antioxidants are essential for maintaining the quality of food and prolonging its shelf life by reducing oxidative damage caused by free radicals. To assess the antioxidant activity of the samples, two extensively used assays, DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging tests, were applied (Fig. 3a). The limited antioxidant activity seen in samples without essential oil may be ascribed to the intrinsic characteristics of the constituent elements that make up the micro-nanofibers. The polymer matrix of the micro-nanofibers is composed of G, Ch, and PVA, all of which exhibit inherent antioxidant characteristics.

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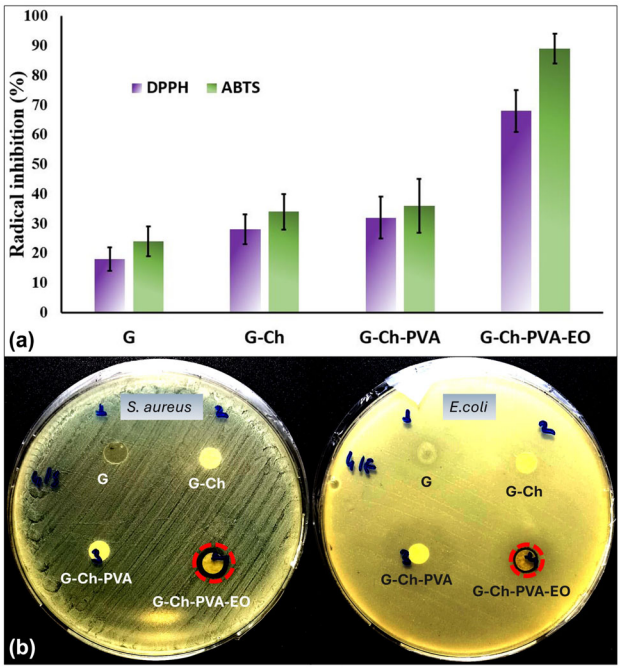


Figure 3 Antioxidant (a) and antimicrobial (b) activities of the samples.

Gelatin, derived from collagen, contains amino acids like proline and glycine, which possess antioxidant properties due to their ability to scavenge free radicals and bind metal ions (Gómez-Guillén *et al.*, 2011). Chitosan, a polysaccharide derived from chitin, has antioxidant activity due to its reactive amino and hydroxyl groups that can donate hydrogen atoms to free radicals, thereby reducing their reactivity Ngo & Kim (2014). Additionally, the physical structure of the micro-nanofibers may contribute to their antioxidant activity by offering a large surface area for interaction with free radicals. The findings demonstrated a considerable boost in antioxidant activity with the addition of EO into the micro-nanofiber matrix.

The micro-nanofibers containing EO (G-Ch-PVA-EO) demonstrated markedly enhanced antioxidant activity, as evidenced by the notable rise in both DPPH and ABTS radical scavenging percentages. Specifically, the DPPH radical scavenging activity rose from 32% in G-Ch-PVA to 68% in G-Ch-PVA-EO, while the ABTS radical scavenging activity increased from 36% in G-Ch-PVA to 89% in G-Ch-PVA-EO. These results underline the powerful antioxidant activity of EO, likely due to its rich content of phenolic components such as carvacrol and thymol. Carvacrol and thymol are well-known for their strong antioxidant effects, ascribed to their ability to donate hydrogen atoms to free radicals, therefore neutralising their reactivity and alleviating oxidative stress (Chroho *et al.*, 2024). The observed increase in antioxidant activity may potentially be related to the synergistic interactions between EO and the polymer matrix, which might boost the storage and bioavailability of the bioactive components (Moustafa *et al.*, 2023). Overall, the findings reveal the potential of EO-incorporated micro-nanofibers as excellent antioxidant-based food packaging materials, giving both functional and protective capabilities for boosting the quality and safety of packaged food items.

Antimicrobial activity

The antimicrobial activity of micro-nanofibers is crucial in food packaging, where ensuring microbial safety is paramount for extending shelf life and maintaining the quality of packaged food products. To evaluate the antimicrobial activity of the samples, two common foodborne pathogens, *S. aureus*, and *E. coli*, were used in the disk diffusion method. Although gelatin and chitosan are known to exhibit antimicrobial activity individually (Pereda *et al.*, 2011), the samples without essential oil (G, G-Ch, and G-Ch-PVA) did not exhibit significant antimicrobial activity against either *S. aureus* or *E. coli*, as evidenced by the absence of inhibition zones in the disk diffusion assay (Fig. 3b). The reason for these results may be due to several factors such as concentration, interaction with other components, and environmental conditions. Further studies are warranted to elucidate the specific mechanisms underlying the antimicrobial activity of the polymer matrix and to optimise the formulation for enhanced efficacy. In contrast, micro-nanofibers containing essential oil (G-Ch-PVA-EO) exhibited remarkable antimicrobial activity against both *S. aureus* and *E. coli*, as evidenced by the presence of clear inhibition zones in the disk diffusion assay. This could be attributed to the synergistic effects of major ingredients (carvacrol, thymol, and caryophyllene) in EO with the polymer matrix. Each of these compounds was extensively studied for their antimicrobial efficacy against a wide range of microorganisms. Carvacrol and thymol, in particular, have been shown to disrupt microbial cell membranes, inhibit microbial enzyme activity, and interfere with microbial cell signalling pathways, resulting in potent antimicrobial effects (Chroho *et al.*, 2024). These results highlight the potential of essential oil-incorporated micro-nanofibers as effective antimicrobial food packaging materials for inhibiting the growth of foodborne pathogens and ensuring the microbial safety of packaged food products. By harnessing the antimicrobial properties of natural essential oils, it is possible to develop eco-friendly and sustainable food packaging solutions that reduce reliance on synthetic antimicrobial agents and contribute to the preservation of food quality and safety.

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Figure 4 Appearance of tomatoes treated with micro-nano fibres during the storage period.

Packaging performance studies on tomatoes

Appearance

The appearance of tomatoes coated with the fibrous samples throughout the storage period is depicted in Fig. 4. As the duration of storage progressed, the tomatoes exhibited an increase in redness indicative of ripening. However, noteworthy differences emerged among the various sample groups, particularly evident on the 15th and 20th days, despite their similar initial visual appearance. By the conclusion of the storage period, significant mould growth was observed in the control sample. Conversely, in sample G, noticeable wrinkling attributed to moisture loss was observed. Notably, the tomato sample coated with the G-Ch-PVA-EO displayed the least alteration during storage which can be attributed to the antioxidative and antimicrobial properties of EO.

Weight loss

The process of weight loss in fruits and vegetables is directly connected to their respiration, which involves the loss of moisture and the release of volatile chemicals (Locali-Pereira *et al.*, 2021). Throughout the storage time, all kinds of fibrous mats showed varying degrees of weight reduction, suggesting the evaporation of moisture and the possibility of tomatoes being spoiled. Nevertheless, it is important to mention that the weight loss seen in the fibrous mats was very little in comparison to the control (unpackaged tomatoes). This suggests that packaging materials based on fibrous mats successfully minimise the moisture loss and preserve the quality of the packaged tomatoes. The relationship between the reduction in weight of tomatoes and their respiration rate may be elucidated by analysing the influence of packing materials on the regulation of gas exchange and the permeability of moisture. Tomatoes undergo respiration, which involves the emission of carbon dioxide and the consumption of oxygen. This process causes changes in the internal gas composition and moisture content. Efficient packing materials must strike a compromise between facilitating gas exchange to avoid anaerobic conditions and minimising moisture loss to prevent dehydration (Buendía−Moreno *et al.*, 2019). Micro/nanofiber-based packaging materials, namely those using EO (G-Ch-PVA-EO), have shown exceptional efficacy in preserving the quality of tomatoes via the reduction of weight loss (Table 3). This finding indicates that the antibacterial and antioxidant characteristics of EO may have had a role in preventing spoiling by regulating the respiration rate of tomatoes.

Firmness

Firmness is a critical parameter in evaluating the quality and texture of tomatoes, directly influencing consumer perception and acceptance. As the storage period progressed, significant variations in firmness were observed among the sample groups (Table 3). By day 5, the firmness of the control sample decreased by approximately 5.5% compared to the accepted baseline, while the fibrous mats-coated tomato sample containing essential oil (G-Ch-PVA-EO) showed a decrease of only about 3.7%. Further decreases in firmness were observed by day 10, with the control sample exhibiting a decrease of approximately 38.4% compared to the first day of storage. In contrast, the nanofiber-treated tomato sample containing essential oil maintained a higher firmness, showing a decrease of only about 21.9%. By day 15 and day 20, significant differences in firmness were evident among the sample groups. The control sample displayed the most pronounced decrease in firmness, with reductions of approximately 62.2% and 70.7%, respectively, compared to the first day. In contrast, the fibrous mats-coated tomato sample containing essential oil (G-Ch-PVA-EO) consistently exhibited higher firmness values, showing reductions of only about 37.2% (10.3 N) at day 15 and 50% (8.2 N) at day 20, respectively. These results underscored the potential of fibrous mats-based coatings, particularly those incorporating EO, in preserving the firmness and texture of tomatoes during storage.

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pH

pH value is also a crucial parameter in evaluating the acidity or alkalinity of food products, with implications for flavour, safety, and shelf life. Throughout the storage period, a general trend of increasing pH values was observed across all sample groups (Table 3). This increase in pH is consistent with previous studies reporting that the pH value of tomatoes tends to rise with prolonged storage time, ripening, and respiration (Al-Dairi *et al*., 2021). The observed increase in pH values during storage aligns with findings by Aragüez *et al*. (2020)), who noted a similar trend of pH increase in tomatoes during storage, attributed to the effect of increased oxygen levels on fruit respiration rate. This suggests that biochemical reactions and microbial activity occurring during storage may contribute to the observed changes in acidity, leading to alterations in pH values over time. By day 15 and day 20, significant differences in pH were evident among the sample groups. The control sample displayed the highest pH values, with values of 4.46 and 4.61, respectively, indicating a more pronounced decrease in acidity compared to the nanofiber-treated tomato samples. In contrast, the tomatoes coated with fibrous mats maintained relatively lower pH values, ranging from 4.23 to 4.51, suggesting better preservation of acidity and flavour. While the exact mechanisms underlying the pH changes in the tomatoes coated with fibrous mats warrant further investigation, it is plausible that the antioxidative and antimicrobial properties of EO in the micro-nanofiber coatings may have mitigated microbial growth and biochemical changes, thereby influencing pH values during storage.

Microbial load

Microbial load is crucial for assessing the microbiological quality and safety of food products, providing insights into the presence and proliferation of potentially harmful microorganisms. The microbial count results for mesophilic aerobic bacteria, yeast, and mould in tomatoes coated with nanofibers during the storage period are shown in Table 3. As the storage period progressed to day 20, notable differences in microbial counts were observed among the sample groups. The control sample displayed the highest microbial counts for both mesophilic aerobic bacteria and yeast and mould, with values increasing to 5.12 log CFU g^{-1} and 8.63 log CFU g^{-1}, respectively. These findings suggest a significant proliferation of microorganisms in the control sample over the storage period, likely due to the absence of protective coatings. In contrast, the nanofiber-treated tomato samples exhibited lower microbial counts compared to the control, indicating the potential antimicrobial effect of the nanofiber coatings. Specifically, the nanofiber-treated tomato sample containing essential oil (G-Ch-PVA-EO) showed the lowest microbial counts for both mesophilic aerobic bacteria (3.76 log CFU g^{-1}) and

Table 3 Quality characteristics of tomatoes during the storage period

Storage (day)	Sample	Weight loss (%)	Firmness (N)	pH	Mesophilic aerobic bacteria (log CFU g^{-1})	Yeast and mould (log CFU g^{-1})
0		–	16.4 ± 2.4	4.08 ± 0.5	3.16 ± 0.11	1.32 ± 0.12
5	Control	1.5 ± 0.2^{a}	15.6 ± 2.3^{a}	4.12 ± 0.2^{a}	–	–
	G	1.2 ± 0.1^{b}	15.3 ± 3.6^{b}	4.24 ± 0.3^{a}	–	–
	G-Ch	1.3 ± 0.1^{b}	14.9 ± 4.2^{b}	4.21 ± 0.2^{a}	–	–
	G-Ch-PVA	0.9 ± 0.1^{c}	15.1 ± 1.6^{b}	4.09 ± 0.1^{a}	–	–
	G-Ch-PVA-EO	1.1 ± 0.1^{b}	15.7 ± 2.1^{a}	4.11 ± 0.3^{a}	–	–
10	Control	2.2 ± 0.2^{a}	10.1 ± 2.6^{d}	4.19 ± 0.2^{a}	–	–
	G	2.1 ± 0.1^{a}	10.9 ± 1.3^{c}	4.31 ± 0.2^{a}	–	–
	G-Ch	1.5 ± 0.2^{b}	11.8 ± 2.4^{b}	4.29 ± 0.1^{a}	–	–
	G-Ch-PVA	1.4 ± 0.1^{b}	12.1 ± 2.5^{b}	4.26 ± 0.2^{a}		
	G-Ch-PVA-EO	1.6 ± 0.2^{b}	12.8 ± 1.6^{a}	4.21 ± 0.3^{a}	–	–
15	Control	4.3 ± 0.2^{a}	6.1 ± 0.6^{c}	4.46 ± 0.3^{a}	–	–
	G	3.8 ± 0.3^{b}	7.6 ± 0.4^{b}	4.42 ± 0.2^{a}	–	–
	G-Ch	3.3 ± 0.1^{c}	10.1 ± 2.4^{a}	4.25 ± 0.2^{b}	–	–
	G-Ch-PVA	3.1 ± 0.3^{c}	9.9 ± 1.6^{a}	4.29 ± 0.2^{b}	–	–
	G-Ch-PVA-EO	2.9 ± 0.4^{c}	10.3 ± 2.2^{a}	4.23 ± 0.1^{b}	–	–
20	Control	5.2 ± 0.3^{a}	4.8 ± 0.6^{d}	4.61 ± 0.1^{a}	5.12 ± 0.31^{a}	8.63 ± 0.23^{a}
	G	4.9 ± 0.2^{a}	5.3 ± 0.2^{c}	4.51 ± 0.2^{b}	5.02 ± 0.13^{b}	6.92 ± 0.21
	G-Ch	4.1 ± 0.1^{b}	7.4 ± 0.3^{b}	4.43 ± .0.3^{b}	3.92 ± 0.16	5.23 ± 0.16^{d}
	G-Ch-PVA	3.9 ± 0.4^{b}	7.3 ± 1.1	4.35 ± 0.2	4.07 ± 0.13	5.47 ± 0.09^{c}
	G-Ch-PVA-EO	3.2 ± 0.1	8.2 ± 0.6^{a}	4.28 ± 0.2	3.76 ± 0.14	3.91 ± 0.14

Different letters indicate statistically significant differences ($P < 0.05$) between samples on the same storage day.

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yeast and mould (3.91 log CFU g^{-1}) at day 20. This observation suggests that the incorporation of EO into the nanofiber matrix may have contributed to inhibiting microbial growth and proliferation, thereby preserving the microbiological quality of the tomatoes. The correlation between microbial counts and other analysis results has indicated the influence of microbial activity on the quality and shelf life of the tomatoes. For instance, the higher microbial counts observed in the control sample correlated with softer texture and higher pH values, indicative of microbial degradation and metabolic activity.

Conclusions

The study focused on using an electro-blowing method to effectively develop fibrous structure-based active food packaging material and give active characteristics to the package by incorporating EO. Neat G, G-Ch, G-Ch-PVA, and G-Ch-PVA-EO micro-nanofibers were successfully produced. The findings are summarised as follows:

- Nanofibers were produced with a mean diameter of 210.77 ± 3.32 nm and 578.20 ± 21.91 nm for G and G-Ch samples, respectively. However, with the addition of PVA and EO the fibre diameters increased from the nano to micro scale.
- The antioxidant activity of the samples was enhanced with the addition of EO into the micro-nanofiber matrix. By the incorporation of EO, a notable rise in both DPPH and ABTS radical scavenging percentages was observed. Specifically, the DPPH radical scavenging activity rose from 32% in G-Ch-PVA to 68% in G-Ch-PVA-EO, while the ABTS radical scavenging activity increased from 36% in G-Ch-PVA to 89% in G-Ch-PVA-EO.
- Fibrous packaging materials, especially G-Ch-PVA-EO, have shown exceptional efficacy in preserving the quality of tomatoes via the reduction of weight loss. In addition to high firmness values, reductions of only about 37.2% and 50%, respectively, indicate improved preservation of texture and quality. As well as low microbial counts for both mesophilic aerobic bacteria (3.76 log CFU g^{-1}) and yeast and mould (3.91 log CFU g^{-1}) at day 20 were also recorded.

All these results highlight the potential advantage of encapsulating EO into novel hybrid fibrous materials for active food packaging applications.

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Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

Ethics approval was not required for this research.

Peer review

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Data availability statement

Data will be made available on request from the corresponding author.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Supporting Information.
Fig. S1. Thermal effect on G-Ch nanofibrous mats.
Fig. S2. FTIR analysis of micro-nanofibers mats.
Fig. S3. Thermal characteristic of micro-nanofibrous mats.
Fig. S4. Results of contact angle and air permeability analyses of the micro-nanofibrous mats.

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