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Original article

A new application for the valorisation of pomegranate seed oil: nanoencapsulation of pomegranate seed oil into electrospun nanomats for food preservation

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Summary Pomegranate seed oil (PSO) contains many bioactive materials including antimicrobials, antioxidants, tocopherol and unsaturated fatty acids such as punicic acids. Utilising PSO with nanotechnological ways is a novel approach. Therefore, in this study, PSO-loaded nanomats having an average diameter of 327 nm with 97.6% encapsulation efficiency were produced. Then, the protection potential of nanomats was determined in terms of the microbial and oxidative deterioration of food samples. On the 1st day of storage, the TMAB load of the control kashar cheese was 4.35 log CFU g^{-1}, while it was 3.05 log CFU g^{-1} in the coated cheese (change: 1.3 logs). On the 20th day of storage, the TMAB load of the CK sample and PSc sample was 5.52 and 4.22 log CFU g^{-1}, respectively (change: 1.3 logs). For fish fillets, nanoencapsulated PSO enabled a bacterial reduction of 1.22 log cycles after 9 days of storage. The total mould and yeast number of cheese samples increased during storage, but the increase was lower in the coated group. Nanomats also increased the oxidative stability of food samples. Thiobarbituric acid values of coated samples were lower than uncoated samples.

Keywords Electrospinning, fish fillet, kashar cheese, nanoencapsulation, pomegranate seed oil.

Introduction

Food preservation has been the basis of food processing technology since ancient times. Delaying microbial spoilage and oxidative deterioration in foods has been one of the most important issues in food science. Many methods such as drying, food additives and coating application (Ilter *et al.*, 2008; Ceylan *et al.*, 2018) are used for food preservation. Due to the tendency to focus on healthy foods, the use of natural materials has become widespread to reduce microbial spoilage, provide oxidative stability of foods and increase their functional properties. Many studies have been carried out on the fortification of natural products as antioxidant and antimicrobial agents in foods (Yemiş & Candoğan, 2017; Meral & Erim Köse, 2019).

Pomegranate (*Punica granatum* L.) is a fruit that has high production rate in many different cultures for thousands of years. The pomegranate seed, which make-up approximately 3% of the weight of the pomegranate, is a by-product of the food industry and it contains approximately 12–20% oil (in dry weight). Pomegranate seed oil (PSO) contains 65–80% of conjugated fatty acids. The most important of these are 9-trans, 11-cis, 13-trans, octadecatrienoic acid, which is called punicic acid (Drinić *et al.*, 2020). Moreover, it has been noted that the antioxidant properties of cold-pressed PSO are significantly higher than red wine, green tea, and the synthetic antioxidant butylated hydroxyanisole (BHA) (Siano *et al.*, 2016). In addition to antioxidant properties, PSO could limit the development of the total mesophilic aerobic bacteria (TMAB) (Ekin *et al.*, 2019). Therefore, the usage of PSO as an antioxidant and antimicrobial agent is important for both waste valorisation and for obtaining natural food additives. However, due to the presence of conjugated double bonds, PSO is susceptible to oxidation, in particular, the presence of air, moisture, light and heat (Cortez-Trejo *et al.*, 2021). In this respect, nanoencapsulation which is obtained by the electrospinning method may be an effective tool that will be used both for the protection of the PSO from light, heat, air and the valorisation of PSO. In the electrospinning process,

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the polymer solution is exposed to a high electric field and sprayed on the collector plate on the opposite side with the aid of a pump. Thus, stable nanofibres or nanoparticles having nano-size can be obtained for pharmaceutical and food coating applications (Meral *et al*., 2019a; Ceylan *et al*., 2020b). Different bioactive substances can be separately or simultaneously integrated into the interior or exterior of the nanofibre structures. Thus, extended surface area providing many advantages including higher effectiveness with less material and contact with the wider food surface can be obtained (Rostamabadi *et al*., 2020; Ceylan *et al*., 2021).

Therefore, the aim of this work was the nanoencapsulation of PSO into polyvinylalcohol (PVA)-based nanomats through electrospinning for potential application as a food coating agent. In this study, we used foods having different nutritional components such as fish fillets and kashar cheese to test the protective effect of PSO-loaded nanomats. The fish and cheese were coated with nanomats. Then, the microbial load and oxidation parameters during the cold storage period were determined. In this sense, this study was the first study fabricating the PSO-loaded nanomats and determining their effects on some quality parameters of cheese and fish fillets.

Materials and methods

Material

PSO was purchased from Arapaş Arifoğlu Marketing Distribution and Trade Inc. (İstanbul-Turkey). PVA, Tween 20, (Sigma-Aldrich, St. Louis, MO, USA), Plate Count Agar, (PCA), and Dichloro Rose Bengal Agar (DRBC) (Merck, Darmstadt, Germany) were used in the analysis.

Nanomat fabrication and the application of nanomats on food samples

PVA (10% w/v) solution was prepared and was stirred at 80 °C for 4 h. The 10 mL of PVA solution was mixed with 0.5 mL of PSO and 0.1 mL of Tween 20 for 1 h with the aid of a magnetic stirrer. Then the mixture was taken into a syringe for using the electrospinning process. An electrospinning system consisting of a high voltage unit, syringe pump unit, the flat collector was used (Fytronix ESP-900 Electrospinning System, Elazığ-Turkey) to fabricate nanomats from PVA solution containing PSO. During the electrospinning process, the different voltages, tip to collector distances and flow rates were used to obtain nano-sized and beadless nanomats. Nanomats were collected on a metal collector covered by aluminium foil. Approximately 10-mg nanomats were collected on the aluminium foil and the PSO amount in the nanomat (10 mg nanomat) was calculated to be 0.471 mg. After fabrication, nanomats were characterised and used to coat food samples. One foil was used to coat each sample. Kashar cheese and fish fillets were obtained from a local market found in Van-Turkey. Rainbow trout fishes were purchased at a local store in Van, Turkey, and transported to the laboratory under refrigeration conditions. The fish samples were washed with tap water and the skin and bone were removed. Fish samples were cut into eight fillets. Fresh packaged kashar cheese was aseptically cut into cubes with 20 cm^2 of surface and an average weight of 20 g $\pm$ 5 g. Twenty grams of kashar cheese and fish fillets were wrapped with aluminium foils which were covered with approximately 10-mg PSO-loaded nanomats. Unwrapped cheese and fish fillet were used as control samples, and the control samples were coded as CK and CF, respectively. The wrapped cheese and fish samples were coded as PSc and PSf, respectively. All the samples were finally stored at 4 °C at different times. For kashar cheese, microbial and TBARS analyses were carried out at times 1, 3, 6, 13 and 20 days, while these analyses were done at times 1, 3, 7 and 9-day for fish samples.

Scanning electron microscopy

The morphologies of produced nanomats were analysed using a scanning electron microscope (Supra 35 VP; Carl Zeiss, Oberkochen, Jena, Germany), after coating with a thin layer of gold. SEM image was used to measure nanomat diameters using ImageJ software.

Attenuated total reflection Fourier transform infrared spectroscopy

Molecular structures of the nanomats were observed using an attenuated total reflection Fourier transform infrared (ATR-FTIR) spectrophotometer (Bruker Optics, Billerica, MA, USA) in the wavenumber range of 4000–400 cm^{-1}. The spectra were recorded with 16 scans.

Differential scanning calorimetry

Two to five milligrams of nanomat were used for determining the thermal profiles by using a differential scanning calorimetry (DSC) instrument (Bakher, Germany). The temperature range of 25 °C–350 °C at a heating rate of 10 °C min^{-1} was used for analysis.

Viscosity measurement

The viscosity of the dope solution of blending was measured by using Brookfield DV-III Ultra

programmable rheometer (Brookfield Engineering Laboratories Inc, Middleboro, MA, USA) with a small sample adapter and spindle SC4-27. The viscosity measurements were done at 25 °C.

Encapsulation efficiency

Nanomats were diluted 1:10 (w/v) using n-hexane to release the encapsulated compounds. The mixture was centrifuged at 5000 g for 30 min. After centrifugation, the absorbance of the supernatant was recorded at 370 nm. The EE was determined using the following equation:

$$\text{Encapsulation efficiency} = \frac{\text{Total PSO Amount} - \text{Free PSO Amount}}{\text{Total PSO Amount}} \times 100$$

Microbial analyses

To determine the effects of PSO-loaded nanomats on microbial growth, total mesophilic aerobic bacteria count (TMAB) and total yeast mould count (TMY) were determined in all samples. For microbial counting, 225 mL of sterile 0.85% saline water were added to the 25 g of samples and homogenised in a stomacher (Stomacher 400, Seward, London, England), then an aliquot of 0.1 mL was taken and dilutions were made to further count the microorganisms by using the spread plate method. Petri dishes were incubated for TMAB count at 30 °C for 24–48 h and TMY count was incubated at 25 °C for 72–120 h. Subsequently, the counts of microorganisms were expressed as log CFU g^{-1}.

Thiobarbituric acid value

Thiobarbituric acid (TBARS) distillation method was performed as described by (Tarladgis *et al.*, 1960). Results were expressed as mg malondialdehyde per kg (mg MDA kg^{-1}).

Data analysis

Duncan's multiple range test was performed to determine the effect of nanomat application on microbial growth and oxidation parameter by using SPSS 11.0 (SPSS Inc., Chicago, IL, USA).

Result and discussion

Electrospinning parameters

In the electrospinning process, the processing parameters directly affect the morphology of nanomats. The diameter, shape and homogeneity of the nanomaterials depend on different factors such as type of polymer, the concentration of polymer in the dope solution, type of solvent used to dissolve of polymer, flow rate, voltage and distance. The production of homogenous and bead-free nanomat is critical in the electrospinning process, and the selection of electrospinning parameters is so important to produce nanomats with lower diameter and bead-free (Ceylan *et al.*, 2020b). Therefore, we determined each electrospinning parameter by preliminary tests. Different electrospinning parameters have been tested to fabricate the nano-sized and beadless material. The voltage values changing from 15 to 27 kV, flow rates (0.04–1.2 mL min^{-1}) and tip-to-collector distances (10–15 cm) were used. As a result; the flow rate, voltage and distance were determined to be 0.04 mL min^{-1}, 24 kV and 11.5 cm, respectively. Yilmaz *et al.* (2020) stated that the electrospinning parameters to obtain alginate-based nanofibres were flow rate of 1.2 mL h^{-1}, a distance of 10 cm and voltage of 22 kV. In another study proposed by Meral *et al.* (2019) to produce nisin-loaded nanomats, flow rate, distance and voltage were 1.2 mL h^{-1}, 8 cm and 20 kV, respectively. Vafania *et al.*, (2019) fabricated nanofibres from chitosan/gelatin solutions. The 25 kV voltage and, 5 cm distance (tip-to-collector) were used to obtain nanofibres. In the electrospinning process, process parameters may differ because of the differences in the study design. Therefore, the parameters should be determined and optimised for each study.

Characterisation of PSO-loaded nanomats

The viscosity of the dope solution was determined as 875 mPas. Surendhiran *et al.*, (2020) determined the viscosity of the electrospun solution as 731 mPas. The SEM images of PVA-based and PSO-loaded nanomats are given in Fig. 1a–c. The PSO-loaded nanomats were almost bead-free, smooth and homogeneously distributed. As could be seen from Fig. 1, uniform nanomats were formed. Also, it was observed the PSO was encapsulated to PVA-based nanomats. The encapsulated structures were shown in the section taken from Fig. 1c. The diameter for the PSO-loaded nanomat was in the range of 270–347 47the range of or the PSOure 1CAlso, it was observed the PSO was encapsulated toin diameter. Several studies reported the diameter of nanostructures was increased due to the integration of bioactive materials within nanostructures. Vafania *et al.* (2019) reported that incorporation of thyme essential oil in chitosan-gelatin nanofibres led to an increase in the mean fibre diameter from 148 to 343 nm. Similarly, Yilmaz *et al.* (2020) found that the diameter of nanofibre increased from 345 nm to 842 nm, indicating that the successfully

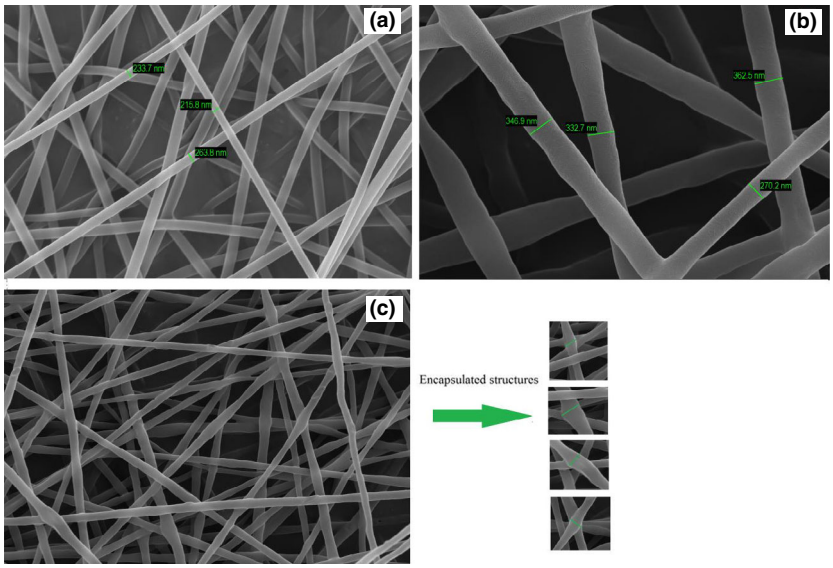

Figure 1 Scanning electron microscopy image of nanomats. (a) PVA-based nanomats. (b and c) PVA based PSO loaded nanomats.

nanoencapsulation within the nanostructures. As a result, SEM images confirmed that nanomats with an average diameter of 323 nm were produced from the dope solution with a viscosity of 875 mPas and that the PSO was encapsulated into the nanomats.

DSC analysis was performed to determine the thermal stability of PSO-loaded nanomats. DSC thermogram of the PSO, PVA and PSO-loaded PVA-based nanomats are represented in Fig. 2.

An endothermic peak of around 40 was detected in PSO, the endothermic peak temperature rose to 60 , in PSO-loaded nanofibres. The result indicated the nanoencapsulation improved the thermal resistance of PSO. In the PVA-based nanomats, two endothermic peaks observed around 125 , and 180 correspond to the melting and decomposition of PVA, respectively. The peaks shifted from 125 to 140 , and from180 to 190 by nanoencapsulation. In the PSO-loaded nanomats, also, an exothermic peak is observed around 125 , indicating an exothermic reaction caused by crystallisation.

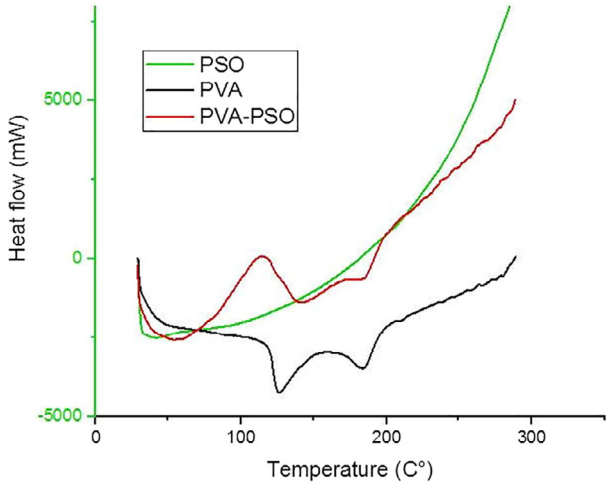

Figure 2 Differential scanning calorimetry thermogram of PSO, PVA and PSO-loaded nanomats.

The ATR-FTIR spectra of nanomats are presented in Fig. 3. A very broad peak around 3300 cm^{-1} was determined PVA and PVA-based and PSO-loaded nanomats and it was attributed to OH stretching, which may be caused by PVA or water (Ertürk & Meral, 2019). The main peaks of PVA-PSO-based nanomats were observed at, 2926, 2857, 1734, 1435, 1372, 1248 and 1090 cm^{-1}. The peak at 2926 cm^{-1} was attributed to CH_2 asymmetric stretching vibration (Kharazmi *et al.*, 2015). A sharp peak corresponded to the C=O carbonyl stretching was determined at 1734 cm^{-1} (Fadhil *et al.*, 2019; Cortez-Trejo *et al.*, 2021). The band could indicate the presence of fatty acids and punicic acid. However, the same peak was determined in pure PVA. But, the intensity of the band was increased in the PVA-PSO which means the presence of more carbonyl sites. The peak could indicate the encapsulation of PSO in nanomats. C-O stretches were observed at 1248 cm^{-1} and 1090 cm^{-1}. The peak was determined 1435 cm^{-1} corresponded to CH deformation and aromatic ring vibration. The band at 1372 cm^{-1} corresponded to the vibration of single bond OH (Chupin *et al.*, 2013). Symmetric C-O stretching was found at 1090 cm^{-1} (Liu *et al.*, 2015). In the fingerprint region, two peaks were observed at 990 and 947 cm^{-1}. The bands were assigned to C=C

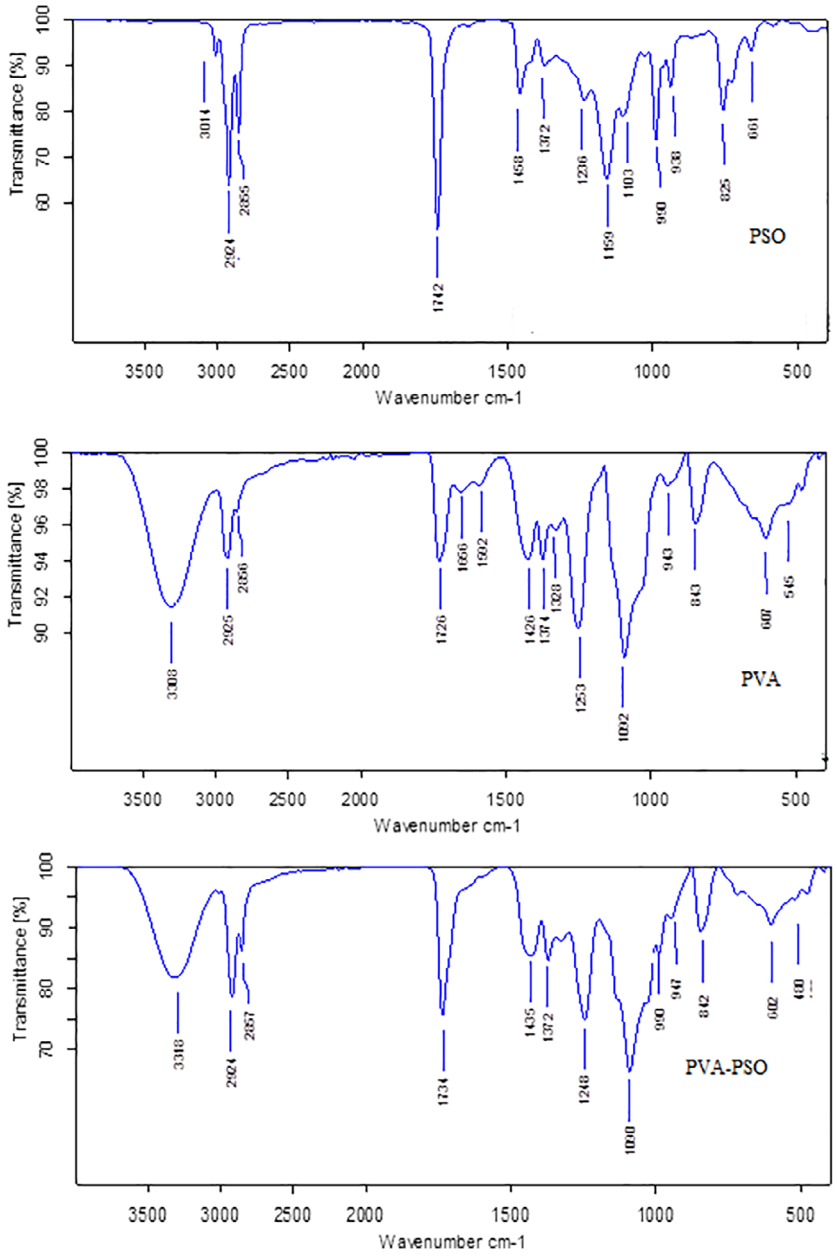

Figure 3 ATR-FTIR spectrum of PSO, PVA and PSO-loaded nanomats.

bending. The bending vibration of the C-H bond was determined at 842 cm^{-1} (Wang *et al.*, 2009). When viewed using the naked eye, it was seen that the PVA and PSO-PVA graphs were similar to each other. However, two small peaks at 1592 and 1666 cm^{-1} in the PVA diminished or disappeared because of interaction between PVA and PSO. Also, the intensity of some peaks was increased or shifted. As a result, characterisation of PSO-loaded nanomats was done by using ATR-FTIR, and nanoencapsulation of PSO was also confirmed.

Encapsulation efficiency

In this study, the encapsulation efficiency was found to be 97.6%. This value was very high and it indicated that almost all of the PSO taken into the dope solution was loaded into the PVA-based nanomats. High encapsulation efficiency is one of the important advantages that can be achieved with the electrospinning technique, which is a system that solvent in the dope solution evaporates in a short time. High encapsulation efficiency (above 95%) were also reported in

previous studies performed by using the electrospinning system (İnanç Horuz & Belibağlı, 2018; Horuz & Belibağlı, 2019; Kurd *et al*., 2019; Karim *et al*., 2020).

Microbial growth

Figure 4 demonstrates the TMAB and TMY load of cheese and fish samples. The TMAB load of both samples gradually increased during the cold storage period. On the 1st day of storage, the TMAB load of the control kashar cheese (CK) was 4.35 log CFU g^{-1}, while it was 3.05 log CFU g^{-1}in the coated cheese (change: 1.3 logs). On the 20th day of storage, the TMAB load of the CK sample and PSc sample was 5.52 and 4.22 log CFU g^{-1}, respectively (change: 1.3 logs). Different results have been reported related to the TMAB load of kashar cheese. According to Yıldız Akgül *et al*., (2019), while the minimum TMAB load of kashar cheese was 4.3 log CFU g^{-1}, the maximum TMAB load was 7.41 log CFU g^{-1}. In another study, the TMAB in cheese samples was found to be 7.04 and 8.05 log CFU g^{-1}. It also was found that the TMAB load of cheese fluctuated during cold storage days. On the 30th day of storage, the TMAB load was 7.7 log CFU g^{-1} but it decreased to 7.3 log CFU g^{-1} on the 60th day of storage (Yangilar and Oğuzhan Yildiz, 2016). Civelek & Cagri-Mehmetoglu (2019) found that TMAB counts in passively packed cheeses increased approximately 2 log on day 14 and then decreased 1 log. In this regard, our results are consistent with previous studies, but the TMAB load of cheese samples differs from the above-mentioned studies due to raw milk quality and the differences in the initial TMAB load of milk. TMAB and TMY load of fish fillets are illustrated in Fig. 4. On the 1st day of storage, the TMAB count of the control fish fillet (CF) was determined to be 3.35 log CFU g^{-1}. It was 2.98 log CFU g^{-1} for the coated fish fillet (PSf). During the storage period, the TMAB load of coated fish fillets was lower than those of the control group samples. TMAB load of the CF sample was reached to 6 log CFU g^{-1} which is considered as unfit for human consumption on the 7th day of storage, on the same day, the TMAB load was 4.97 log CFU g^{-1} for coated fish samples. On the 9th day of the storage period, the TMAB load was 7.4 log for control and 6.18 log for Psf. 1.22 log difference was recorded between the two samples after 9 days of storage. Our previous studies investigated the effects of nano-nisin and nano-thyme oil on the microbial growth of fish fillets. In this regard, at the end of the storage period, approximately 2 log reductions were obtained with the nano-nisin application, and 1 log reduction was recorded nano-thyme treatment compared with the untreated samples. In this study, the results were consistent with our previous studies demonstrating that nano-application limited microbial growth. As could be seen, PSO-loaded nanomats significantly reduced the TMAB load of kashar cheese and fish fillets. TMAB load of fish fillets was less reduced by nanomat application according to kashar cheese. Differences between fillets and cheese samples can be explained as follows. Firstly, the microbial flora of each food group is different. One of the well-known factors affecting microbial growth is the nutritional composition of the food. Also, food processing conditions affect the growth and reproductive rates of microbial cells. In this context, it was expected the microbial load would be different for the two groups. On the first day of storage, while the TMY count in the control group fish samples was 2.87, it was found to be 2.81 log CFU g^{-1} in the coated group. During storage, the TMY load increased, but the increase was lower in the coated group. After 9 days of storage, the TMY load of coated fish samples was (4.91 CFU g^{-1}) lower than the control group with 6.29 log CFU g^{-1}, and it meant a 1.38 log limitation was obtained. A similar trend was observed in kashar cheese samples. The average TMY population of cheese increased during storage for 20 days. However, coating with PSO-loaded

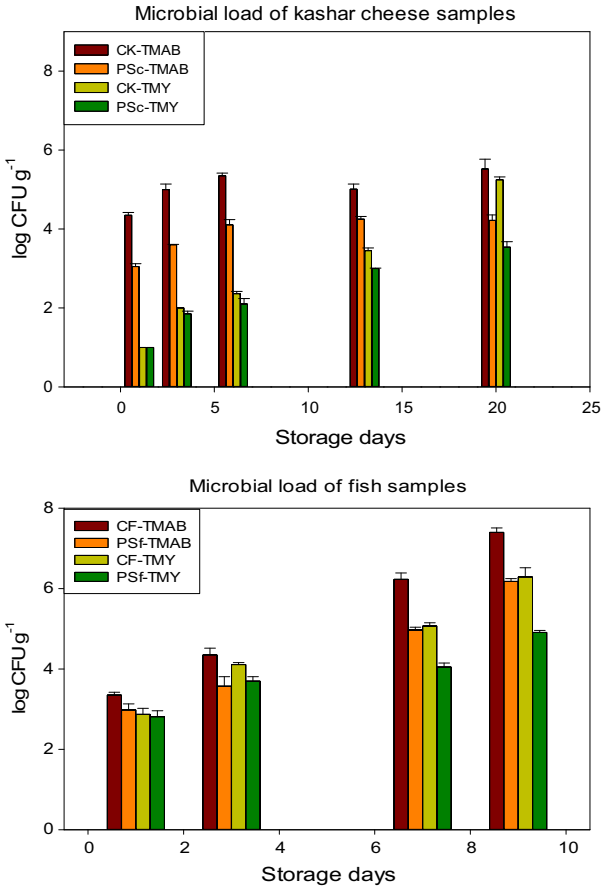

Figure 4 Microbial load of kashar cheese and fish samples.

nanomats effectively delayed the growth of total mould and yeast load of cheese after 20 days ($p < 0.05$). In particular, on the 20th day, the coating application showed a significant reduction of TMY load of cheese, and their reduction level was 1.71 log CFU g^{-1} compared to control ($P < 0.05$). Öksüztepe *et al.*, (2009) reported that the TMY load of vacuum-packed kashar cheese varied between 1.0 and 2.62 log CFU g^{-1}. In this study, it was shown that microbial growth could be limited by nanomat application. It was reported that PSO exhibited antimicrobial activity against *Escherichia coli, Bacillus subtilis, Listeria monocytogenes* and yeast (Sogut *et al.*, 2019; Lu *et al.*, 2020). According to Kanatt *et al.* (2010), pomegranate peel extract (PE) exhibited good antimicrobial action against pathogen bacteria including *Bacillus cereus* and *Staphylococcus aureus*. Also, the shelf life of chicken meat products extended by 2–3 weeks due to the addition of PE. Since PSO had an antimicrobial effect, microbial limitation was expected. However, when we compare our results with the results of previous studies, it was seen, we obtained a more effective result with less material. For example, Fernandes *et al.* (2017) added the microencapsulated rosemary oil into the cheese samples at the 0.5% oil concentration. Then, they investigated that the effects of microencapsulated rosemary oil on microbial growth. They obtained a bacterial limitation of 1.36 log at 3 days of storage. They reached the bacterial limitation with the 5 mg rosemary oil. Viacava *et al.* (2018) used the thyme essential oil (TO) as an antimicrobial agent to evaluate the effect of TO on the microbial limitation of minimally processed lettuce. For this purpose, lettuce samples were dipped in solutions containing different levels of TO. (TO1: 0.5 g TO L^{-1}, TO2: 1 g TO L^{-1}, and 1.5 g TO L^{-1}). Compared to our study with previous studies done by Viacava *et al.*, (2018) and, Fernandes *et al.* (2017), it appeared that we achieved a similar limitation of microbial growth with the lower amount of oil. In this study, 10 mg of nanomat was used to coat the fish fillet and cheese samples, and the amount of PSO in nanofibre was calculated to be 0.471 mg. As can be seen, with nanotechnology it was possible to spread a small amount of oil over a surface of 20 g-sample, and with such a low amount of oil, a 1 log reduction was recorded for the TMAB load for fish and cheese samples. Nanomat treatment was effective to limit microbial count and it was determined the important reduction at the end of the storage period as compared to control samples.

TBARS

Secondary lipid peroxidation products can be determined by TBARS analysis, which indicates the formation of MDA, for example. Therefore, in this study, TBARS was determined. TBARS values of kashar cheese samples increased during storage. However, this increase was slower in PSc samples. TBARS value, which was 1.31 for CK at the beginning of storage, was determined as 1.96 at the end of storage. These values were determined as 0.25 and 1.42 mg MDA kg^{-1} for PSc samples, respectively. The effect of PSO-loaded nanomats on TBARS value was observed even on day 1 of storage, and there was a 5-fold difference between the TBARS values of the two samples (CK and PSc) (Fig. 5). In a study determining the effect of zein films containing gallic acid-catechin on lipid oxidation of kashar cheese, it was revealed that the TBARS values of uncoated kashar cheeses varied between 0.73 (day 1) and 1.2 (day 35) mg MDA kg^{-1} during storage. In the same study, it was stated that TBARS values in the coated samples with zein films containing gallic acid-catechin varied between 0.45 and 0.66 mg MDA kg^{-1} (Ünalan *et al.*, 2013). TBARS values of fish samples were also given in Fig. 5. TBARS values of fish samples fluctuated during storage. In the initial storage days, TBARS values were

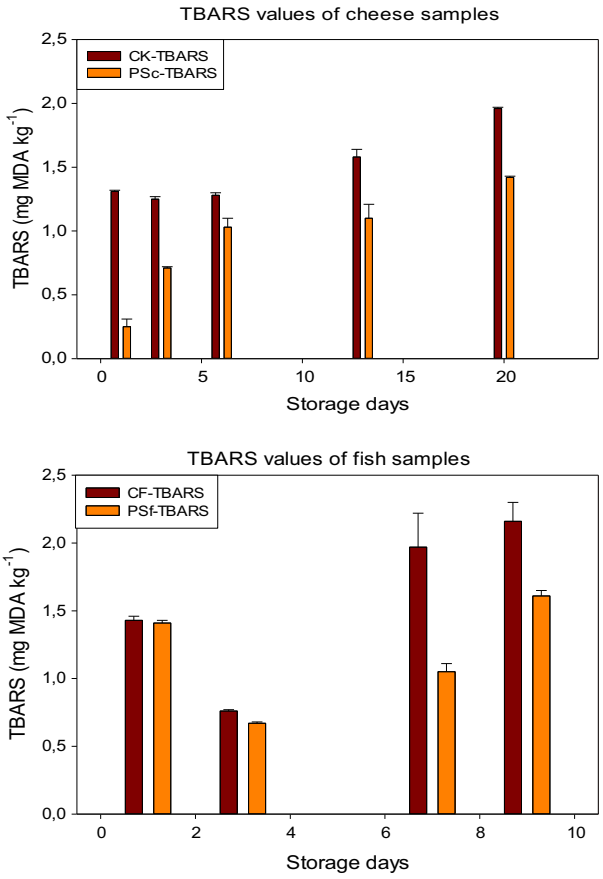

Figure 5 TBARS values of kashar cheese and fish samples.

similar in both samples, but with the progression of the storage period, obvious differences were determined between CF and PSf samples. On day 3, the TBARS value of the control (CF) and coated fish fillet (PSf) samples was lower than those of other storage days, probably due to unstable compounds resulting from primary oxidation that rapidly degraded into secondary oxidation products including aldehydes and alcohols (Han & Song, 2021). At the end of the storage period, TBARS increased. The initial value of TBARS was 1.43 mg MDA kg^{-1} and the CF sample showed the greatest TBARS value (2.16 mg MDA kg^{-1}) at the end of storage. It could be attributable to the degradation products of hydroperoxides and peroxides produced during the oxidation process of unsaturated fatty acids (Sun *et al.*, 2019). The TBARS value of the sample coated with PSO-loaded nanomats was lower than that of the uncoated control samples during the storage period. Consequently, lipid oxidation in the fish fillet and kashar cheese samples coated with PSO-loaded nanomats was delayed because of the antioxidants such as phenolic compounds, punicic acid and tocopherol which could chelate metals and inhibit lipoxygenase. Zafer Ceylan & *et al.*, (2020) determined that phenolic compounds and tocopherol found in nanoemulsions containing wheat germ oil (WGO) retarded the oxidation of cooked-fish samples. In this study, PSO-loaded nanomats could protect fish fillets and kashar cheese from oxidation by forming a barrier to oxygen permeability in treated samples during the cold storage period. The results indicated that nano application could be effectively used to prevent lipid oxidation in food.

Conclusion

In this study, nanomats were developed using PVA and PSO, which were fruit processing by-products. The loading of PSO in nanomats significantly reduced the microbial load of food samples. At the end of the storage period, while 1.3 log reductions were observed at the TMAB load of kashar cheese, the reduction was 1.2 log for fish fillets. Additionally, upon application of the developed nanomats, the fish fillets and cheese samples coated with the nanomats showed a lower degree of lipid oxidation as compared to the control samples. Overall, our findings indicate that nanomats loaded with PSO have the potential to be used as a coating material to retard lipid oxidation and to limit microbial growth on the food surface.

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Conflict of interest

The authors declare that they have no conflict of interest.

Author Contributions

Nazan Kutlu: Data curation (equal); Formal analysis (equal); Investigation (equal). **Mehmet Mustafa Ekin:** Data curation (equal); Formal analysis (equal). **Raciye Meral:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Project administration (equal); Software (equal); Supervision (equal); Writing – review & editing (equal). **Yağmur Erim Köse:** Data curation (equal); Formal analysis (equal). **Zafer Ceylan:** Conceptualization (equal); Data curation (equal); Investigation (equal).

Data Availability Statement

The authors elect to not share data.

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