

Sustainable pectin/rosemary oil-loaded solid lipid nanoparticles film for packaging applications: Shelf-life insights for ready-to-eat chicken breast

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ABSTRACT

This study proposes a novel hybrid hydrocolloid film using pectin and rosemary oil-loaded solid lipid nanoparticles (RO-SLN), integrating a biodegradable matrix with nanoencapsulated bioactive compounds to create a sustainable and effective active packaging system for extending the shelf life of ready-to-eat (RTE) chicken breast. Tween 20 (TSRO) and pectin (PSRO) stabilized RO-SLN, which was characterized by size (154 and 415 nm), polydispersity index (0.246 and 0.482), and zeta potential (−27 and −38 mV). PSRO was most effective at reducing the hydration properties of pectin films compared with the CS film (water vapor permeability, 97%; moisture content, 51%; and solubility in water, 47%), confirming superior moisture-barrier performance of the dried film without food contact. Shelf-life efficiency was tested for RTE chicken breast stored at 4 ± 1 °C for 7 days. RO-SLN had enhanced antibacterial and antioxidant activity. Samples wrapped in pectin/RO-SLN films had a longer antimicrobial (5–7 days) and antioxidant (2–5 days) shelf life than the control (no film). Additionally, pectin/RO-SLN films did not significantly change pH ($p < 0.05$) during the entire storage. TSRO increased weight loss in RTE chicken breast by 13% on day 7. However, panelists' perception, rather than the sample's intrinsic quality, influenced the sensory shelf life. Pectin/PSRO films maintained acceptable scores for all sensory attributes at the end of storage. Overall, this approach offers insights into the potential of pectin/RO-SLN films to extend the shelf life of RTE chicken breast and may support the development of clean-label alternatives to synthetic preservatives.

1. Introduction

The rising demand for ready-to-eat (RTE) foods, combined with growing concerns about food quality amid globalization, continues to increase. RTE foods require no further preparation and can be consumed immediately after opening. However, their shelf life is limited. For instance, RTE chicken breast is highly susceptible to bacterial contamination and oxidative deterioration, resulting in undesirable sensory and nutritional qualities (Nikmaram et al., 2018). The global RTE chicken breast market is projected to grow from USD 2452.7 million in 2025 to USD 4500 million by 2035 (WiseGuyReports, 2026). Slowing the growth of undesirable microorganisms and preventing lipid oxidation in RTE chicken breast underscores the need to develop innovative preservation

methods. For instance, packaging materials can incorporate bioactive compounds. In this context, plant extracts such as essential oils (EO) are gaining wide interest in the food industry for their potential as antimicrobials and antioxidants. These are natural, Generally Recognized as Safe (GRAS) food additives and meet consumers' expectations for clean-label products, rather than synthetic preservatives (Nikmaram et al., 2018).

Salvia Rosmarinus, or *Rosmarinus officinalis* L., known as rosemary, is an aromatic plant often used in a variety of cuisines and is among the herbs with the highest antioxidant activity. Rosemary essential oil (RO) contains 95–98 wt% monoterpenes and their derivatives, and 2–5 wt% sesquiterpenes. RO has antibacterial, antimicrobial, antifungal, and anti-inflammatory activity (Chetia et al., 2025). RO has been used as a

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food preservative and flavoring agent, and its effect on the shelf life extension of food products has been confirmed. Additionally, RO has been incorporated into several biopolymeric matrices to produce edible films that positively affect food shelf life, as recently reviewed (Yang et al., 2023). Despite the huge potential of RO for food preservation, its specific characteristics, such as being volatile, hydrophobic, and aromatic, affect its application. Encapsulating RO offers an effective way to address the limitations of using it directly in food and/or packaging materials. Researchers have encapsulated RO in various nanocarriers, including nanoemulsions (Shahrampour & Razavi, 2023), nanogels (Mohsenabadi et al., 2018), and solid lipid nanoparticles (Saporito et al., 2018), to enhance its bioactivity. Despite the bioactive potential of RO-loaded solid lipid nanoparticles being exploited in the pharmaceutical field, e.g., wound healing (Saporito et al., 2018), antioxidant capacity (Lacatusu et al., 2010), and skin gel (Montenegro et al., 2017), scarce literature considers their incorporation into a biopolymeric-based matrix to obtain sustainable active packaging materials. Furthermore, future research should prioritize mature, scalable RO encapsulation that addresses key industrial and market demands, such as controlled release, cost efficiency, and consumer acceptance (Yang et al., 2023).

Solid lipid nanoparticles (SLN) are nanocarriers composed of food-grade solid lipids stabilized with emulsifiers, typically ranging from 50 to 1000 nm. Their highly ordered crystalline structure enables efficient encapsulation of bioactive compounds, including hydrophobic and hydrophilic molecules such as EO. SLN have shown unprecedented potential to increase the stability, bioavailability, and functionality of EO. Practically, SLN represents an alternative and improved colloidal nanocarrier to conventional nanoemulsions, liposomes, and polymer-based nanoparticles (Pascuta & Vodnar, 2022). Furthermore, SLN are biocompatible and biodegradable, with low-cost production and ease of wide-ranging production (Assefi et al., 2023). EO-SLN for food preservation have been incorporated into hydrogels and coatings, but research remains limited and in its early stages. Safaeian Laein et al. (2024a) prepared an alginate coating activated by *Zataria multiflora* EO-SLN to preserve chicken fillets. The same research group also prepared a gelatin coating containing peppermint EO-SLN to preserve trout fillets during cold storage. Fincheira et al. (2024) prepared chitosan/polyvinyl alcohol hydrogels incorporating *Oreganum vulgare* and *Thymus vulgaris* EO-SLN to control the growth of *Botrytis cinerea* and *Penicillium expansum*, phytopathogenic fungi that cause fruit deterioration. Vakili-Ghartavol et al. (2024) treated strawberries with *Mentha × piperita* L. EO-SLN to improve antimicrobial activity, shelf life, and quality. Additionally, literature on using EO-SLN as reinforcement for biopolymeric-based films is scarce or even nonexistent.

Pectin, among biopolymers, is a viable option for sustainable packaging due to its abundance in nature, outstanding film-forming capability, high biocompatibility, flexibility, and gelling ability. Pectin films offer good oxygen barrier properties but are highly sensitive to water, with high water vapor permeability and water solubility (Martău et al., 2019). Incorporating lipids can further functionalize pectin films and reduce these weaknesses. Pectin-EO films represent a promising approach for developing more innovative and sustainable food packaging due to their antimicrobial and antioxidant properties. However, their practical application is limited by the volatility and rapid release of EO, which compromises stability over time and hinders industrial scalability (Ainani et al., 2026). Encapsulating the liquid lipid phase within SLN before incorporating it into pectin films offers an effective strategy to enhance stability and modulate release behavior, thereby improving the system's overall functionality. Recently, researchers reinforced pectin films with beeswax SLN, improving their water vapor permeability and mechanical properties (J. Xie et al., 2023). Furthermore, differently stabilized SLN, acting as active or inactive fillers, were used to tailor the protein films (Verena Wiedenmann et al., 2019).

While many active pectin/EO packaging films exist (Ainani et al., 2026), few address the synergistic effects of physical, antimicrobial, sensory efficacy, and oxidative stability in extending the shelf life of RTE

chicken breast, and none combine RO-SLN with a pectin matrix, as investigated in this study. A key new insight is the comparative evaluation of pectin films activated by free RO and RO-SLN, as active (RO-loaded pectin-stabilized SLN) and inactive (RO-loaded Tween 20-stabilized SLN) fillers, revealing how nanoparticle emulsifiers affect the preservation efficacy of RTE chicken breast over 7 days of refrigeration (4 ± 1 °C) storage. This work advances knowledge in sustainable food packaging by integrating nanoencapsulation, biopolymer technology, and a panel-focused formulation strategy. Since the previous work provides a comprehensive physical, mechanical, thermal, and morphological characterization of developed pectin/RO-SLN films (Pascuta et al., 2026), this study provides new perspectives on the use of EO-SLN as functional fillers in biopolymeric-based films, demonstrating their role in improving the efficacy of EO, while bridging the gap between food shelf life extension and consumer demand for clean-label alternatives to synthetic preservatives for healthy reasons.

2. Materials and methods

2.1. Materials

Soy lecithin, “Emulpur IP,” was purchased from Cargill Texturizing Solutions (Hamburg, Germany). Tristearin was procured from IOI Oleo GmbH (Hamburg, Germany). Sucrose palmitate was purchased from Alfa Aesar, ThermoFisher GmbH (Karlsruhe, Germany). Tween 20 (Polyoxyethylene sorbitan monolaurate) was procured from Sigma-Aldrich (St. Louis, Missouri, USA). Glycerol (glycerin 99.5%) was purchased from Analar Normapur, BDH Prolabo (München, Germany). Citrus pectin with DE 45% and galacturonic acid content of 88% (CU-L 103/21) was kindly delivered by Herbstreith & Fox GmbH & Co (Neuenburg, Germany). Rosemary oil (Rosemarinoel Aroma nat.) was provided by Symrise (Nördlingen, Germany). Calcium chloride anhydrous was purchased from Carl Roth GmbH + Co (Karlsruhe, Germany). All solutions were prepared in distilled water. Fresh chicken breast was kindly delivered by Transavia S.A.

2.2. Characterization of rosemary oil

The Supplementary File (Table 1S) presents the qualitative analysis of the rosemary oil volatile profile and the minimum inhibitory concentration (MIC). The main volatile compounds were expressed as % of the total peak area. MIC results expressed the antimicrobial potential of rosemary oil against *S. aureus*, *C. parapsilosis*, *C. zeylanoides*, and *S. enterica*. Table 2S presents the remaining volatile compounds at concentrations below 1%.

2.3. Preparation of rosemary oil-loaded solid lipid nanoparticles

SLN were prepared by ultrasound-assisted hot emulsification according to Verena Wiedenmann et al. (2019), with slight modifications. Briefly, soy lecithin (0.125 g) and tristearin (1.5 g) were heated under stirring to 80 °C (30 min). 1.0 g of RO (25 °C) was added, and continue for an additional 1 min. Then, 22.375 g of 3.02% sucrose palmitate (w/w) in 5 mM phosphate buffer (pH 6.0) was added at 80 °C. A sonicator (Bandelin Sonoplus, HD 2022) with a titanium tip (Bandelin electronic, D-12207, UW 2200, MS 73, Germany) at an amplitude of 75% in pulsed mode (0.5 s pulse length) was used for the emulsification process. During sonication (30 min), the temperature was maintained at 60 °C.

To prepare TSRO, the emulsion was poured into an 8% Tween 20 solution (w/w), preheated to 60 °C (1:1), and immediately cooled to 20 °C in ice water under continuous stirring. To prepare PSRO, first prepare a pectin solution. Gradually dissolve 2 g of pectin (w/w) in 98 g (w/w) hot distilled water (90 °C) using an Ultraturrax (Polytron® PT-MR6100 D, Kinematica, Switzerland) at 9500 rpm for 5 min. The speed was increased to 17,500 rpm for another 5 min. Finally, equal amounts of

emulsion and pectin solution (at 60 °C) were vortexed at 2500 rpm for 20 s. The mixture was then immediately cooled to 20 °C in ice water under continuous stirring.

2.4. Characterization of solid lipid nanoparticles

The particle size and zeta potential of SLN are reported in the Supplementary File, Table 3S. Differences between TSRO and PSRO were discussed in more detail in previous work (Pascuta et al., 2026).

2.5. Film preparation

Pectin films were produced according to the method of Nisar et al. (2018), with modifications. 2% (w/w) pectin was dissolved in hot distilled water (90 °C) already containing glycerol (30% w/w of pectin) and was homogenized with an Ultraturrax at 9500 rpm for 5 min. 2% CaCl₂ solution (w/v) was added to reach 1% dry mass of CaCl₂ (w/w of pectin). Then, the homogenization speed was increased to 17,500 rpm for an additional 5 min. The foam was removed with a spoon. The obtained hot solution was mixed with TSRO/PSRO emulsion (40% w/w, 25 °C) at 9500 rpm for 2 min using the Ultraturrax. Then, an ultrasonic bath (Bandelin Sonorex Digitec, DT 100 H, 35 kHz, Germany) was used to remove air bubbles (42 ± 1 °C, 10 min). The film solution was immediately poured into polyethylene Petri dishes (9 cm diameter) with a constant dry mass of 0.6 g and a constant pectin content of 1.8%. Films were dried at room temperature (25 ± 1 °C) and stored under these conditions for at least 4 days before characterization and application to ready-to-eat chicken breast. For pectin films with free RO (CRO), RO (0.8% w/w) was directly added to the pectin solution during homogenization at 9500 rpm for 5 min, followed by a cycle of 17,500 rpm for 5 min using the Ultraturrax.

2.6. Characterization of films

The visual appearance was observed by capturing digital images of pectin-based films before further characterization and application to RTE chicken breast.

Film thickness (mm) was determined using a micrometer (Mausier, Pfeiffer Instrument, Germany). Five random values were noted for each film, and the measurements were conducted in duplicate (n = 2).

Moisture content and water solubility were determined by gravimetric analysis. For moisture content, film pieces (2 cm²) were weighed before and after drying at 102 °C to reach a constant dry mass, and the result was expressed as a percentage of the initial weight. For water solubility, film pieces (2 × 2 cm) were dried over calcium chloride and weighed precisely. Each film sample was immersed in 25 mL of distilled water and agitated at 300 rpm (30 min/25 °C), then filtered through pre-weighed Whatman No. 1 paper. The filters were weighed again after drying at 60 °C for 24 h and cooling in a desiccator. Solubility was expressed as the percentage of dissolved film material.

Water vapor permeability (WVP) was measured following ASTM E96/E96M-10. Permeability cups containing anhydrous CaCl₂, with a 6 mm air gap between the CaCl₂ and the film (10 cm² exposed to water vapor), were placed in a pre-equilibrated desiccator containing a saturated NaCl aqueous solution at 25 ± 1 °C (75% RH). A linear regression ($R^2 < 0.996$) was generated by plotting weight gain against time (grams/hour). The slope was divided by the exposed film area (0.001 m²) to calculate the water vapor transmission rate (WVTR). For WVP, we first calculated the water vapor partial pressure difference (WVPP) at the underside of the films using the Correction for Resistance due to Still Air and Specimen Surface equation described in ASTM E96/E96M-10. Then, WVP was calculated by multiplying WVTR by film thickness and dividing by the WVPP between the two sides. Mean values from five points per film were used for thickness (Teleky et al., 2022).

2.7. Film application on RTE chicken breast

The fresh chicken breasts were cut into slices with a height of a maximum of 1 cm and grilled without salt and spices to obtain ready-to-eat (RTE) chicken breasts. Pieces of RTE chicken breast with a minimum weight of 25 g were packaged in commercial low-density polyethylene (LDPE) plastic bags with a zip (0.1 mm in thickness), without (CS) or with pectin films containing (i) free rosemary oil (CRO), (ii) TSRO, and (iii) PSRO. Pectin films covered both sides of the RTE chicken breast. Packaged RTE chicken breast was stored at refrigeration conditions (4 ± 1 °C) for 7 days. Appearance, weight loss, pH, and total viable cell count analysis were assessed on days 0, 2, 5, and 7 of storage. Sensory analysis was evaluated on days 0 and 7 of storage.

2.8. Evaluation of RTE chicken breast

2.8.1. Appearance, weight loss, and pH

Appearance of RTE chicken breast during storage time was visually evaluated.

Weight loss was expressed as a percentage of the initial weight of the packaged RTE chicken breast piece. pH of the stored RTE chicken breast was measured using a pH meter (InoLab® Multi 9310 IDS, WTW, Weilheim, Germany) in triplicate (Socaciu et al., 2021). 5 g of RTE chicken breast was dispersed in 45 mL of distilled water by an Ultraturrax at 10,000 rpm for 1 min.

2.8.2. Thiobarbituric acid reactive substances

The thiobarbituric acid reactive substances (TBARS) concentration of the samples was determined according to the modified method of (Socaciu et al., 2021). The sample (2 g) was homogenized with 4 mL of sodium phosphate buffer (pH 7.4) at 21,500 rpm for 30 s using an Ultraturrax. The two mL of trichloroacetic acid (30 w/v) were added and homogenized at 17,500 rpm for 30 s using an Ultraturrax. The homogenate was transferred into a 10-mL volumetric flask, brought to volume with phosphate buffer, and vortexed (Velp Scientifica, Italy). The precipitate was filtered through Whatman No. 1 filter paper, and the filtrate was kept for analysis.

Five mL of the filtrate was mixed with five mL of 2-thiobarbituric acid solution (0.02 M) in a ten mL screw-cap test tube and heated at 90 °C for 20 min in a water bath. Then, the test tube was immediately cooled down in ice. The blank was prepared with four mL of phosphate buffer and one mL of trichloroacetic acid instead of the filtrate. The absorbance of each mixture was recorded at 530 nm using a Multiplate reader spectrophotometer (BioTek® Instruments, Winooski, VT, USA). Quantification of malondialdehyde (MDA) was calculated using a linear calibration curve prepared from 1,1,3,3-tetramethoxypropane ($R_2 = 0.9995$). The TBARS value was expressed as mg MDA/kg meat sample.

2.8.3. Total viable cell count

The total viable cell count (TVC) was assessed following ISO 4833-1:2013 (Socaciu et al., 2021). We homogenized 5 g of each sample with 45 mL of saline solution (0.85% w/v) using an Ultraturrax at 10,000 rpm for 1 min. Pour 1 mL of the dilution onto a plate and add 15 mL of agar medium. The medium and sample were thoroughly mixed. The final two dilutions were used for plate preparation, and this procedure was triplicated. TVC enumeration was performed after incubating the inoculated plates at 30 °C for 72 h and was expressed as colony-forming units (CFU).

2.8.4. Sensory analysis

A hedonic test of RTE chicken breast wrapped in pectin-based films was conducted under normal daylight conditions at the University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca (USAMVCN), Romania, according to ISO 11136:2014. Samples were evaluated by a sensory panel comprising 8 voluntary evaluators (4 women and 4 men, aged 21–31 years) before storage (day 0) and at the

end of storage (day 7). The study followed the laboratory ethical standards of USAMVCN, and informed consent was obtained from each subject before they participated in the study. Additionally, the methodology for this study was approved by the ethics committee of USAMVCN (Ethics approval number: CBE nr. 567/09.06.2026). All participants were adults and were fully informed about the voluntary nature and confidentiality of their participation, as well as the samples, pectin/RO-SLN films, and the study purpose. The samples were assigned unique, anonymous three-digit codes and presented to the panellists in a randomized sequence. Color, smell, aspect, juiciness, and overall acceptability were evaluated using a 9-point hedonic scale (9 – extremely pleasant, 1 – extremely unpleasant). A score of 5 was taken as the lower limit of acceptability (Marzlan et al., 2022). The samples were visually and tactually evaluated, without ingestion required. Plain mineral water was provided for palate cleansing between evaluations. To minimize sensory fatigue and maintain evaluation accuracy, panelists were given a short break between sample assessments (Selin et al., 2025).

2.9. Statistical analysis

Statistical analysis was done using Microsoft Excel 2016 ($p < 0.05$). Results were reported as mean $\pm$ standard deviation. Descriptive analysis and tested data homogeneity (Fmax test) before further analysis. ANOVA: A single factor was used to determine significant differences in the characterization of pectin-based films. ANOVA: A two-factor ANOVA with replication was used to assess the significant effects of time and pectin-based film type on the quality of RTE chicken breast. Means sharing different superscript letters within the same parameter were significantly different according to Tukey's HSD test ($p < 0.05$).

Pearson's correlation coefficient was used to explore linear associations among physicochemical, microbiological, lipid oxidation, and sensory variables. pH, weight loss, TBARS, and TVC measurements from four samples (CS, CRO, TSRO, PSRO) across four storage times resulted in sixteen treatment-storage mean values. We calculated correlations involving color, smell, aspect, juiciness, and overall acceptability using the corresponding mean values from the same sample and storage days, resulting in eight treatment-storage mean values ($p < 0.05$). Pearson correlation analysis was exploratory, and the resulting coefficients were interpreted as associations between variables rather than independent-effect estimates because measurements from the same treatment over storage time represent repeated observations and are therefore not fully independent.

3. Results and discussion

3.1. Characterization of films

Table 1 presents the thickness, moisture content, water solubility, and WVP of pectin-based films. Thickness is an important parameter for examining the moisture barrier of films and is used to calculate water permeability. Thickness values ranged between 60 μm (CRO and TSRO) and 72 μm (CS). These results are consistent with the thickness values of pectin-beeswax/citral films (Kashiri, 2025). The lowest thickness of CRO and TSRO films was related to RO volatilization during film drying, as previously reported in the literature (Li et al., 2022). However, a thicker PSRO film was attributed to the high viscosity of pectin, which led to stronger RO entrapment (Attallah et al., 2020).

Moisture content and water solubility play an important role in the water-barrier resistance of pectin films under humid conditions. These parameters determine the suitability of pectin films for food packaging and their ability to maintain structural integrity in aqueous food (Kashiri, 2025). Moisture content ranged from $8.46 \pm 0.46\%$ (TSRO) to $17.32 \pm 1.46\%$ (CS). Moisture content significantly ($p < 0.05$) decreased with the addition of free RO and RO-SLN. This decrease was attributed to changes in the percentages of hydrophilic and hydrophobic

Table 1

Thickness, moisture content, water solubility, and water vapor permeability of pectin-based films.

Film	Thickness (μm)	Moisture content (%)	Water solubility (%)	WVP $10^{-10} \cdot \text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$
CS	72 ± 3^a	17.32 ± 1.46^a	97.90 ± 1.60^a	9.54 ± 1.41^a
CRO	60 ± 0^b	14.14 ± 0.81^b	79.10 ± 0.80^c	1.73 ± 0.11^b
TSRO	60 ± 0^b	8.46 ± 0.46^c	83.68 ± 0.60^b	1.08 ± 0.21^{bc}
PSRO	71 ± 2^a	8.90 ± 0.61^c	45.79 ± 0.74^d	0.25 ± 0.02^{cd}

CS – pectin film, CRO – pectin film with free rosemary oil, TSRO – pectin film with rosemary oil-loaded Tween 20 stabilized solid lipid nanoparticles, PSRO – pectin film with rosemary oil-loaded pectin stabilized solid lipid nanoparticles. Data are expressed as mean $\pm$ standard deviation ($n = 2$ for thickness, $n = 3$ for moisture content, water solubility and water vapor permeability). Letters indicate significant differences ($p < 0.05$).

molecules per g dry mass. Pectin was the hydrophilic molecule with a high capacity to bind water, which could explain the highest moisture content in the CS film. Lipids and emulsifiers were the hydrophobic molecules that partially replaced the pectin network, thus reducing the ability of pectin/RO-SLN films to bind water. A similar result was reported when fatty acids were added to pea starch-guar gum films (Saberi et al., 2017).

All pectin films were soluble in water, with water solubility ranging from $45.79 \pm 0.74\%$ (PSRO) to $97.90 \pm 1.60\%$ (CS). PSRO had the lowest water solubility, which was attributed to pectin's ability to form a gel. At the same time, TSRO had higher water solubility than PSRO ($p < 0.05$). Using natural pectin as an emulsifier (in our case, a pectin-pectin gel backbone) maintains emulsion stability and improves gel characteristics. CaCl_2 -crosslinked pectin films are reported to show substantially reduced water solubility; Ca^{2+} , through ionic crosslinking of pectin carboxyl groups, can form “egg-box” junctions, resulting in a denser/less water-accessible matrix (Penhasi & Meidan, 2014). In this study, low-methoxyl pectin and Ca^{2+} were used as the main gelator. In contrast, Tween 20, being a non-ionic emulsifier, does not interact with the pectin backbone, which increases gel porosity and weakens its structure (Huang et al., 2025).

The pectin/RO-SLN films can be suitable for packaging ready-to-eat meat products with low water content, as water evaporates during the cooking process.

WVP is an important factor for evaluating the water barrier properties of films and their application in food packaging. A lower WVP is preferred to limit moisture migration between the food and its surroundings. Therefore, the lower the WVP, the higher the moisture barrier. This contributes to a longer shelf life of packaged food (Teleky et al., 2022). WVP ranged between $9.54 \pm 1.41 \times 10^{-10} \cdot \text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ (CS) and $0.25 \pm 0.02 \times 10^{-10} \cdot \text{g} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ (PSRO). WVP significantly ($p < 0.05$) decreased with the addition of free RO and RO-SLN. RO reduced the WVP of pectin films due to its high content of hydrophobic compounds. Monoterpenes found in RO are lipophilic compounds that reduce the water-binding ability of the pectin matrix. RO-SLN reduced the WVP due to: (i) the hydrophobic nature of lipids and emulsifiers, (ii) the platelet shape of SLN that is a better obstacle to water molecules diffusing through the film (Abdollahi et al., 2012), and (iii) the crystalline lipid nanoparticles, which are more effective than liquid lipid droplets at comparable volumes (Zhang et al., 2022). The difference in WVP between TSRO and PSRO is related to the emulsifier used. Tween 20 is highly hydrophilic and complements the hydrophobic nature of sucrose palmitate and lecithin, supporting a higher WVP value. A detailed discussion related to the water barrier of pectin films via various SLN formulations (including TSRO and PSRO) was reported in a previous work (Pascuta et al., 2026). A decrease in WVP was also

reported with the addition of free SLN in protein films (V. Wiedenmann et al., 2019) and in pectin films (Jiayu Xie et al., 2023). Conventional plastic films have a very low WVP. For instance, a WVP of about $2 \times 10^{-12} \text{ g} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ was reported for polyethylene films (Hong et al., 2022) and $4.5 \times 10^{-11} \text{ g} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ for polypropylene films (da Silva et al., 2022). Although developed pectin films had a higher WVP, adding RO-SLN reduced it by almost an order of magnitude. Furthermore, RO-SLN reduced the WVP of pectin films more effectively than the cinnamon EO-loaded Pickering emulsion (Yu et al., 2024), as reflected in the lower WVP values observed in our study.

3.2. Appearance of films

All developed pectin films, incorporating free RO and RO-SLN, were transparent, with a continuous layer and no pores or cracks (Fig. 1). The film solutions completely covered the surface of the Petri dishes, and when solidified, the films peeled off easily. The two sides of the film looked different: the side facing the casting dish was smooth and shiny, while the other was rough, likely due to water evaporation. CRO was glossier and slipperier, while TSRO and PSRO were duller and softer. The differences in the visual and tactile characteristics of pectin-based films were attributed to the physical state of RO and nanoparticles (e.

g., oil distribution, interfacial organization, matrix-nanoparticle interactions). The glossiness and slipperiness of CRO were attributed to the migration or redistribution of free RO toward the film surface during drying. RO contains hydrophobic compounds that are poorly miscible with the aqueous pectin phase and can modify pectin film surface morphology. Similar results were observed in protein/tarragon EO films (Socaciu et al., 2020). Instead, RO-SLN reduced RO mobility and contributed to the duller, softer appearance perceived in TSRO and PSRO. Morphological characterization showed that TSRO and PSRO appeared rougher than CS. SLN interrupted the specific layered internal structure of pectin films and led to a less regular film matrix (Pascuta et al., 2026).

3.3. Evaluation of RTE chicken breast

3.3.1. Appearance, weight loss, and pH

Fig. 1 presents the appearance of RTE chicken breast with pectin films during storage under refrigeration conditions. Immediately after pectin films were applied to the sample surface, they absorbed water from the RTE chicken breast. This phenomenon is supported by the high water solubility of pectin. Furthermore, the TSRO film began to disintegrate on day 5 of storage. TSRO and PSRO became opaque. Despite the

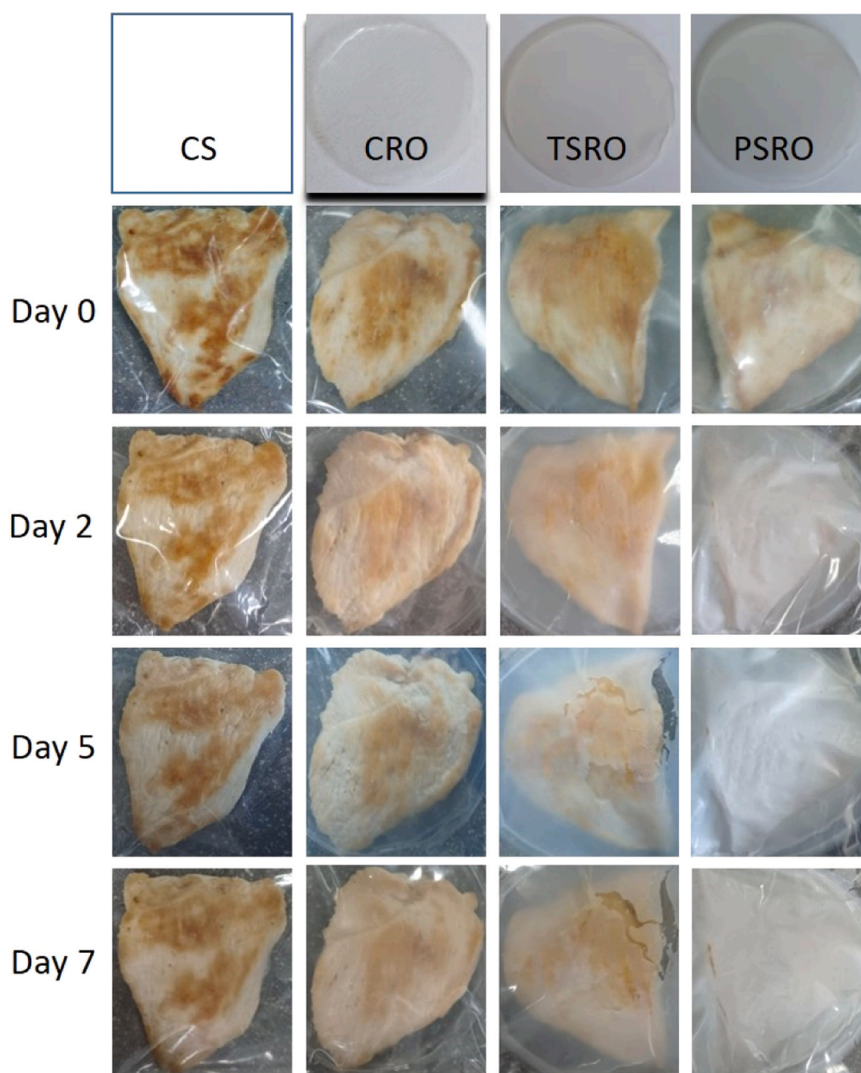


Fig. 1. Appearance of ready-to-eat chicken breast with films during refrigeration storage. CS – sample with commercial bag without film, CRO – sample with commercial bag + pectin film with free rosemary oil, TSRO – sample with commercial bag + pectin film with rosemary oil-loaded Tween 20 stabilized solid lipid nanoparticles, PSRO – sample with commercial bag + pectin film with rosemary oil-loaded pectin stabilized solid lipid nanoparticles.

CRO film also absorbing water from the samples, it remained transparent until the last day of storage. The swelling behavior of the films influenced the opacity of the samples. Water uptake in the films from the RTE chicken breast surface disrupted the initial distribution of the dispersed SLN and altered light diffusion through the films. Hydration and swelling could alter the spatial distribution and could increase local heterogeneity. SLN are platelet-like particles that can obstruct light transmission. In general, a colloidal sample with particle diameters in the visible light wavelength range is more opaque than a sample with smaller particle diameters (Pascuta et al., 2026). Swelling also affected sample weight loss.

Weight loss is a critical analysis for evaluating the water retention capacity of RTE chicken breast during storage. Weight loss increased during storage time in all samples packaged with pectin films. CS exhibited increased weight loss on day 2 and maintained this value until day 7 (Fig. 2A). On the last day of storage, weight loss ranged from $0.34 \pm 0.02\%$ (CS) to $13.57 \pm 0.01\%$ (TSRO) (Fig. 4A). The high weight loss of CRO, TSRO, and PSRO was supported by two steps of water loss. First, according to Alemneh et al. (2025), chicken breast weight loss increased with heat treatment (sous-vide cooking) and storage time at 3°C (from 2 to 10 days). Heat treatment denatured the protein structure and reduced water-holding capacity. Second, pectin is hydrophilic. Consequently, pectin-based films supported interactions between water molecules at the RTE chicken breast surface and the hydrophilic groups in the pectin film matrix, inducing structural changes within the film. Thus, the moisture barrier properties of dried films were changed during food contact. In this study, water released from the RTE chicken breast tissue hydrated the pectin-based films, and water diffused from the sample into the swollen film, resulting in greater weight loss in the packaged samples. Alginate films also increased weight loss in chicken meat during refrigerated storage because of their hydrophilicity (Merenkova & Zinina, 2024).

Changes in pH can indicate meat freshness during storage. The initial pH of RTE chicken breast (6.15) was consistent with the pH (6.19) reported for cooked ground chicken breast without additives (Bae et al., 2020). Across all samples, pH decreased until day 5, then increased slightly by day 7, though it did not exceed the initial pH (Fig. 2B). On day 7, pH ranged between 5.81 (CRO) and 6.08 (TSRO). Although TSRO and PSRO showed lower pH values during storage than CS, these differences were not statistically significant ($p > 0.05$). However, CRO maintained the lowest pH throughout storage ($p < 0.05$). A decrease in pH has been reported in RTE meats packaged with edible films

containing EO (Emiroğlu et al., 2010; Xu et al., 2018). This decrease has been associated with the growth of lactic acid bacteria, the dominant microflora in vacuum-packaged meats. Thus, the pectin films containing RO-SLN had no significant impact on the pH of RTE chicken breast during storage under refrigerated conditions ($p > 0.05$). Most moisture in fresh chicken breast is lost during cooking. Although adding RO-SLN to the pectin film reduced the films' WVP, this was not sufficient in practice. Moisture loss during cooking, combined with the addition of hydrophobic substances, did not preserve the effectiveness of pectin films when applied to RTE chicken breast.

3.3.2. Thiobarbituric acid reactive substances

TBARS serve as an indicator of lipid oxidation, particularly in meat and fish, which reflects the level of MDA in food (Socaciu et al., 2021). TBARS form in the second stage of auto-oxidation, when peroxides are oxidized to aldehydes, ketones, acids, alcohols, and hydrocarbons, which negatively affect sensory attributes and reduce food quality. Lipid oxidation increases with the amount of content (Bertolín et al., 2019). In this study, pectin films were incorporated with lipids to enhance their bioactivity. A key outcome was determining lipid oxidation in wrapped RTE chicken breast using these films as an indicator of shelf life. An MDA value over 0.5 mg/kg indicated some oxidation, while an MDA value above 1.0 mg/kg was considered unacceptable (Reitznerová et al., 2017; Abdullah et al., 2024). Fig. 3 presents the TBARS of RTE chicken breast during refrigerated storage. The initial MDA was 0.33 mg/kg sample, indicating a high-quality meat product with no oxidation occurrence. MDA increased during storage and reached $1.03 \pm 0.01\text{ mg/kg}$ sample (CS) and $1.71 \pm 0.02\text{ mg/kg}$ sample (PSRO) on day 7. CS had the highest MDA values until day 5 and decreased on day 7. This phenomenon may relate to MDA interactions with other food components, such as proteins, during storage, or to additional reactions involving secondary oxidation products, including the formation of other undetected oxidation products besides MDA. A decreased MDA value during storage under refrigeration conditions was observed in wooden breast chicken meat (Rocha et al., 2022). The encapsulation process and SLN emulsifiers influenced antioxidant efficacy. On day 5, CS and CRO exceeded the unacceptable limit of 1.0 mg MDA/kg sample, whereas TSRO and PSRO maintained MDA lower than 0.5 mg/kg ($0.41 \pm 0.06\text{ mg/kg}$ and $0.26 \pm 0.01\text{ mg/kg}$). The decrease in MDA after treatment with TSRO and PSRO was attributed to the increased levels of antioxidant compounds in RO. Tables 1S and 2S present the volatile compounds of RO with antioxidant/antimicrobial properties. Based on the available

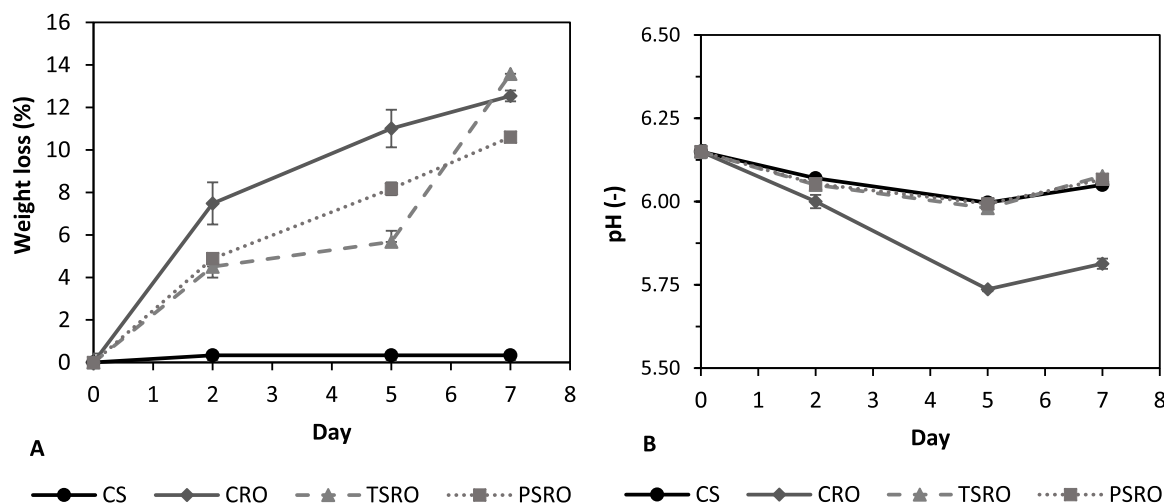


Fig. 2. (A) Weight loss (%) and (B) pH of ready-to-eat chicken breast after 7 days of storage at refrigeration conditions ($4 \pm 1^\circ\text{C}$). CS – sample with commercial bag without film, CRO – sample with commercial bag + pectin film with free rosemary oil, TSRO – sample with commercial bag + pectin film with rosemary oil-loaded Tween 20 stabilized solid lipid nanoparticles, PSRO – sample with commercial bag + pectin film with rosemary oil-loaded pectin stabilized solid lipid nanoparticles. Data were expressed as mean $\pm$ SD ($n = 3$).

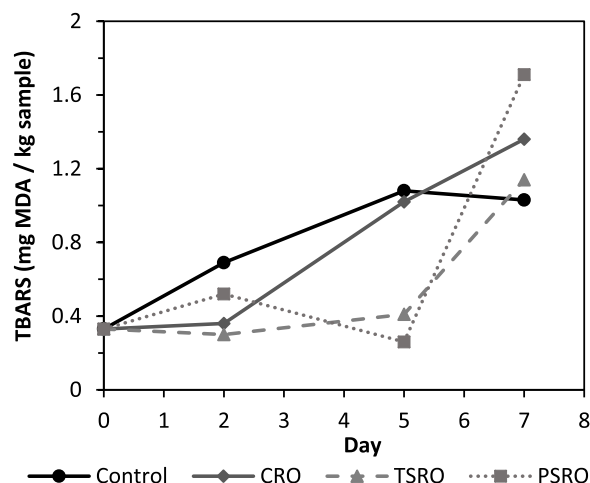


Fig. 3. Changes in thiobarbituric acid reactive substances of ready-to-eat chicken breast during refrigerated storage. CS – sample + commercial plastic bag with zip; CRO – sample + pectin/free RO film + commercial plastic bag with zip; TSRO – sample + pectin/RO-loaded Tween-stabilized SLN film + commercial plastic bag with zip; PSRO – sample + pectin/RO-loaded pectin-stabilized SLN film + commercial plastic bag with zip. Data were expressed as mean $\pm$ SD ($n = 3$).

literature and the MDA values obtained in this study, TSRO and PSRO appeared to release RO more slowly during storage compared to CRO. This behavior may be related to a more controlled release mechanism in pectin/RO-SLN films, which can be hypothesized to involve two sequential steps before RO becomes available in the food system: (i) the migration of RO from the SLN into the pectin matrix and (ii) the subsequent release of RO from the pectin film into the food system (Pascuta & Vodnar, 2022). This suggested mechanism aligns with other research showing that encapsulating EO can improve their antimicrobial and antioxidant properties by protecting their bioactive compounds from environmental degradation. For example, raw chicken fillets treated with an alginate coating activated by *Zataria multiflora* EO-SLN showed lower TBARS values than those treated with a coating containing free EO (Safaeian Laein et al., 2024b). While TSRO had a gradual increase in MDA throughout storage, PSRO had a lower MDA value on day 5 than on day 2. This indicated a delayed or prolonged release of RO from PSRO compared to the more gradual release observed for TSRO. Previous work reported a higher entrapment efficiency for PSRO (93.6%) than for TSRO (82.6%), which can be attributed to the gelling properties of pectin, which form a more stable, protective matrix around RO (Pascuta et al., 2026). Pectin-stabilized systems have been reported to provide improved emulsion stability and encapsulation efficiency due to the formation of a thicker protective interfacial layer (Mohamed et al., 2021; Wang et al., 2017), thus reducing burst release of RO. In the present study, PSRO (415 ± 12 nm, -38 mV) showed a thicker protective layer with controlled RO release than TSRO (154 ± 1 nm, -27 ± 0.4 mV), based on nanoparticle size and zeta potential-based stability (Table 3S). However, because the release kinetics of RO were not directly established in this work, the controlled-release mechanism should be considered an inference based on the observed MDA results and previously published processes. Higher MDA in TSRO and PSRO than in CS at the end of storage was attributed to lipid oxidation in the SLN. Pintado and Cofrades (2020) reported that sausages with reduced fat content and the addition of vegetable oils (as oleogels or emulsion gels) had higher MDA values at the end of storage compared to sausages without the addition of vegetable oils, which agreed with the findings of our study (Pintado & Cofrades, 2020). Thus, the antioxidant capacity of pectin/RO

SLN to improve the quality of RTE chicken breast appeared to be influenced by the encapsulation of RO and the presence of SLN emulsifiers.

3.3.3. Total viable cell count

TVC, also known as the Aerobic Colony Count or Standard Plate Count, indicates quality, not safety, and cannot directly contribute to a safety assessment of RTE food (Health Protection Agency, 2009). The changes in TVC in RTE chicken breast stored under refrigeration for 7 days were evaluated (Fig. 4). The TVC was $2.35 \pm 0.18 \log_{10}$ CFU/g at day 0. This value gradually increased over the storage period for all samples. On day 7, CS exceeded $6.61 \pm 0.04 \log_{10}$ CFU/g and, except on day 2, had the greatest microbial growth during storage. A TVC less than $6 \log_{10}$ CFU/g is usually associated with a mixed flora (Health Protection Agency, 2009). Above this level, a predominant microorganism is present, and acceptability and organoleptic quality are compromised. Wrapped samples with CRO, TSRO, and PSRO were significantly lower (4.82 ± 0.02 , 4.46 ± 0.05 , and $3.63 \pm 0.03 \log_{10}$ CFU/g) on day 7 ($p < 0.05$). The TVC trends were consistent with the differences in release behavior previously discussed in TBARS, differences which may also have contributed to microbial stability during storage. TSRO and PSRO reduced microbial growth, which may be associated with the protective role of SLN and the two-step release of active compounds compared to CRO. Additionally, PSRO showed the best oxidative and microbial stability parameters, attributed to strong entrapment. PSRO had higher encapsulation efficiency than TSRO, attributed to pectin's high viscosity and rapid gel-forming ability (Pascuta et al., 2026). This resulted in a stronger gel matrix than TSRO and was reflected in more efficient inhibition of microbial growth and greater oxidative stability of PSRO on day 5 of storage. Furthermore, higher RO entrapment in PSRO led to higher levels of bioactive compounds, supporting better bioactivity in the developed films. For instance, the main bioactive compound in RO is eucalyptol (1, 8-cineole), with a concentration of 55.7% (Table 1S). Eucalyptol changed the shape and size of Gram-positive and Gram-negative bacteria and supported apoptosis. Eucalyptol is a hydrophobic bicyclic monoterpene that makes bacteria with an outer lipopolysaccharide membrane susceptible to its antimicrobial activity (Mączka et al., 2021). However, the improved antimicrobial activity of RO-SLN should not be attributed only to the SLN protective role and controlled release, especially in a complex food matrix, and requires deeper research for a better understanding. A recent study highlights a complex physicochemical-biological system at the nanoscale as a mechanism of action for improved antimicrobial activity of lipid-encapsulated

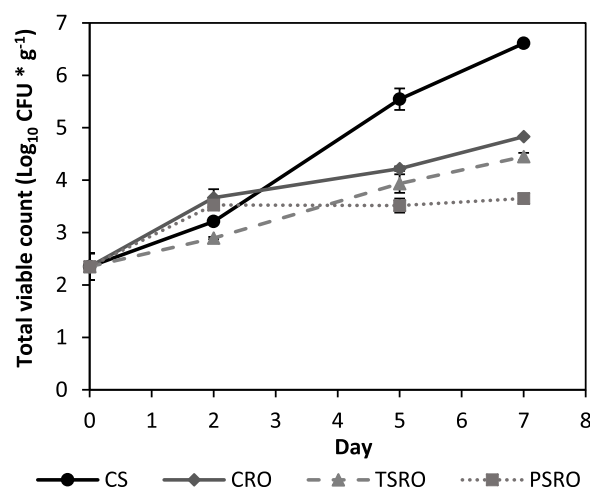


Fig. 4. Changes in total viable cell count of ready-to-eat chicken breast during refrigerated storage. CS – sample + commercial plastic bag with zip; CRO – sample + pectin/free RO film + commercial plastic bag with zip; TSRO – sample + pectin/RO-loaded Tween-stabilized SLN film + commercial plastic bag with zip; PSRO – sample + pectin/RO-loaded pectin-stabilized SLN film + commercial plastic bag with zip. Data were expressed as mean $\pm$ SD ($n = 2$).

bioactives, such as RO-SLN systems. This manuscript provides a comprehensive discussion on recent discoveries of these mechanisms, persistent knowledge gaps, and future perspectives for mechanistic research (Prajapati et al., 2026). Referring to the current study and based on reported work of Prajapati et al. (2026), the mechanism of RO-SLN in reducing microbial growth also involves (i) an enhanced RO-SLN interaction with microbial membranes, (ii) improved solubilization of the hydrophobic part of RO and increased bioavailability; (iii) an intracellular mechanism; and (vi) overcoming antimicrobial resistance to RO bioactivity, due to increased local antimicrobials at the target site and the use of a lower dose. In conclusion, the oxidative and microbial performance of PSRO in increasing the shelf life of RTE chicken breast may be associated with the encapsulation of RO and its improved stability, together with a controlled and sustained release of RO (Wang et al., 2021). In contrast, Tween 20 is a nonionic surfactant that forms a thin interfacial layer around lipid particles, providing less protection against diffusion than the polymeric network formed by pectin. A known disadvantage of SLN is drug leakage and expulsion during storage, due to the complexity of the lipid's physical state and its transition to crystalline form (Mehnert & Mäder, 2012). Furthermore, TSRO may influence the organization of the pectin matrix and potentially facilitate the release of RO from the pectin films onto the sample surface, whereas PSRO appears to be better incorporated within the pectin matrix.

3.3.4. Sensory analysis

The organoleptic properties of RTE chicken breast on days 0 and 7 of storage were evaluated using a 9-point hedonic scale and are presented in Fig. 5. The sensory characteristics, including color, smell, aspect, juiciness, and overall acceptability of the wrapped RTE chicken breast, were examined to assess sensory preference and sensory shelf life. The results showed a decrease in sensory attribute values from day 0 to the end of storage. On day 0, all wrapped samples had lower sensory attribute scores. CRO had unacceptable scores for smell (4.50) and juiciness (4.50), which were below the limit of acceptance, resulting in the lowest overall acceptability score (5.38). TSRO and PSRO had an overall acceptability of 6.88 and 6.00, respectively. These results were attributed to: (i) the concentration of RO that possesses a strong smell that migrated into the sample, according to panelists; and (ii) the swelling effect of the film on the sample surface, which reduced the visibility of the sample through the film. RO is one of the most commonly used EO (flavor and flavoring) in meat and meat products (Li et al., 2023). Fresh chicken breast treated with RO and cooked in an oven for 15 min had a lower smell score before storage (Stojanović-Radić et al., 2018). Hematizad et al. (2021) reported an early negative influence of gelatin-nanochitosan films containing a higher concentration (0.9 v/v) of *Zataria multiflora* Boiss EO on the odor and taste of fresh chicken meat

during refrigerated storage. Research on applying antimicrobial and antioxidant films containing EO to RTE chicken meat remain limited. On day 7, all sensory attributes had lower values compared to day 0. CS had the lowest sensory attribute values compared to wrapped samples, especially for smell (4.88), juiciness (4.63), and overall acceptability (5.38). These were attributed to the presence of spoilage bacteria in CS (according to the TVC result), which may have caused discoloration, acid production, and gas production. Ammonia and amines generated during protein degradation, as well as ketones and aldehydes formed through lipid oxidation, contributed to the sample's unpleasant smell (Hematizad et al., 2021). Except for juiciness, all films maintained the sensory attribute values above 5, which was considered the lowest limit of sensory acceptance. Juiciness was affected by the water absorption of films from the RTE chicken breast. Alginate coating containing *Zataria multiflora* EO-SLN improved the sensory quality of raw chicken fillets (Safaeian Laein et al., 2024c). These results indicate that although CRO, TSRO, and PSRO reduced sensory attribute values, their application – particularly RO-SLN – helps preserve sensory quality during storage of RTE chicken breast.

3.3.5. Determination of shelf life of RTE chicken breast based on physical, microbiological, lipid oxidation, and sensory analyses

Fig. 6 illustrates a strong negative correlation among the physical parameters and a strong positive correlation between microbiological analysis and lipid oxidation ($p < 0.001$), which agrees with the results above. Physical parameters had no significant correlation with microbiological properties, lipid oxidation, and sensory attributes. Microbiological properties and lipid oxidation had a high negative correlation with juiciness, a moderate negative correlation with smell, and no significant correlation with color and overall acceptability. However, sensory attributes showed a strong positive correlation with overall acceptability ($p < 0.01$). These results indicated that panelists' perception of the wrapped sample influenced sensory shelf life more than the intrinsic (physical, microbiological, and lipid oxidation) quality of RTE chicken breast.

Table 2 summarizes the shelf-life results from microbiological and sensory analyses, along with lipid oxidation, for RTE chicken breast wrapped with CRO, TSRO, and PSRO. The microbiological shelf life of all samples wrapped in pectin-based films was extended by two days compared with CS, which was packaged only in an LDPE bag. LDPE is a thermoplastic polymer made by polymerizing ethylene ($\text{CH}_2=\text{CH}_2$), with short- and long-chain branching. LDPE provides passive protection, including excellent water resistance, reflected in the lowest weight loss of CS. LDPE's inert structure lacks functional groups that could interact with or inhibit microorganisms (Moradi et al., 2020). These factors explain the longer microbiological shelf life of CRO, TSRO, and PSRO compared to CS, due to the bioactive compounds in RO. Thus,

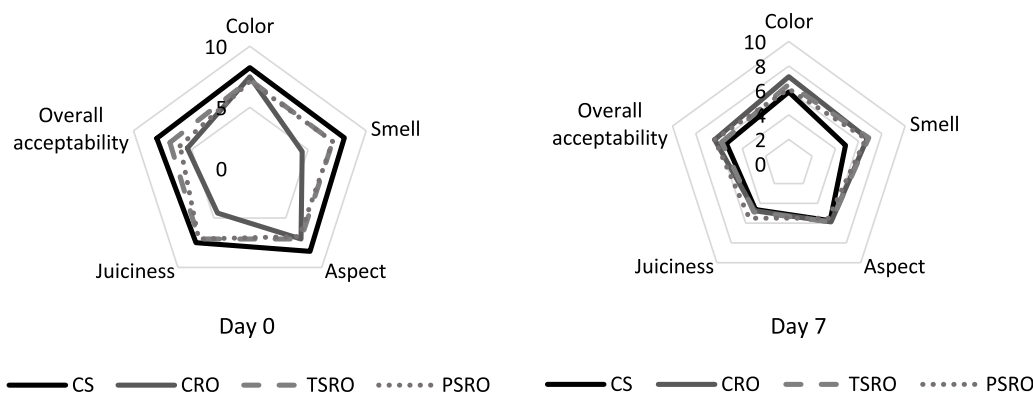


Fig. 5. Sensory analysis of ready-to-eat chicken breast during storage at refrigeration conditions ($4 \pm 1^\circ\text{C}$). CS – sample with commercial bag without film, CRO – sample with commercial bag + pectin film with free rosemary oil, TSRO – sample with commercial bag + pectin film with rosemary oil-loaded Tween 20 stabilized solid lipid nanoparticles, PSRO – sample with commercial bag + pectin film with rosemary oil-loaded pectin stabilized solid lipid nanoparticles.

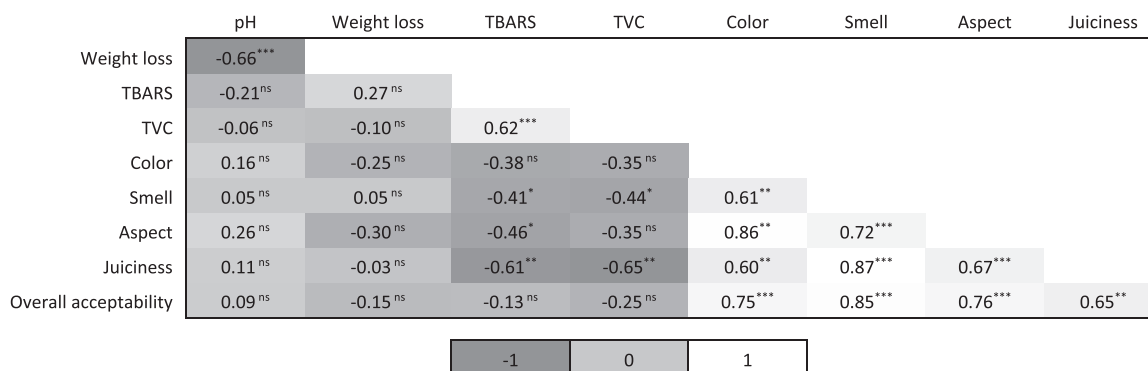


Fig. 6. Pearson correlation among physical and microbiological analyses, lipid oxidation, and sensory attributes of RTE chicken breast. Values with asterisks (*, **, ***) indicate significant differences (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$); values with ^{ns} indicate no statistically significant difference (^{ns} $p > 0.05$).

Table 2

Shelf life (days) of ready-to-eat chicken breast during storage at 4 ± 1 °C.

Treatment	Microbiological analysis ^{a,d}	Lipid oxidation ^{b,d}	Sensory analysis ^{c,d}
CS	5	< 5	-
CRO	7	< 5	-
TSRO	7	5	-
PSRO	7	5	7

^a Based on a microbiological TVC limit value of 6 log₁₀ CFU/g.

^b Based on an MDA value above 1.0 mg/kg sample.

^c Based on the value > 5 for all tested sensory parameters.

^d Data obtained from Figs. 3–5, respectively.

food-contact pectin/RO-SLN films can provide additional protective function to conventional LDPE packaging.

The oxidative shelf life was extended by at least one-two days: for CS and CRO it ended before day 5, TSRO and PSRO maintained it even on day 5. Based on sensory analysis, PSRO films maintained all sensory attributes higher than the unacceptable limit (> 5), resulting in a sensory shelf life of RTE chicken breast of 7 days. This result agreed with the microbiological shelf life. Furthermore, the panelists did not detect changes corresponding to the chemical oxidation measured by TBARS. Although an overall shelf life value could not be established, the microbiological, oxidative, and sensory shelf life indicated that pectin/RO-SLN films could extend the shelf life of RTE chicken breast by at least two days compared with CS wrapped only in an LDPE bag.

3.4. Limitations

Some limitations should be acknowledged and highlighted as important directions for future research. (i) Food safety is an important parameter to consider a complex food-contact packaging system such as pectin/RO-SLN. Therefore, a multidisciplinary approach that combines further microbiological, chemical, physical, and toxicological analyses must also address nanoparticle migration behavior and potential toxicity. (ii) Although pectin/RO-SLN films demonstrated preservative potential, this packaging system significantly increased the weight loss of RTE chicken breast compared to the CS ($p < 0.001$). This effect may represent a techno-economic drawback, especially if the film is intended to be removed before consumption. Regarding product yield, weight loss during storage directly lowers the mass of a product that can be sold and degrades the product's appearance. In terms of juiciness, RTE chicken breast can become drier and feel firmer. Overall, the 13.57% weight loss indicates limited commercial applicability, and future studies should focus on optimizing the developed films. Instead, if the film system is intended for consumption with the food product, further research is required to obtain regulatory approval as a novel food. Sensory quality also remains a relevant challenge, especially given the distinctive visual

appearance and structural changes of the films during storage. Due to water absorption and swelling at the sample surface, the films showed progressive loss of integrity and partial disintegration after day 5 of storage. The edible nature of pectin-based films is compatible with swelling and partial disintegration, although severe disintegration during refrigerated storage may adversely compromise their handling qualities and structural integrity. In this work, this phenomenon is considered a formulation limitation and is mainly explained by the hydrophilic pectin matrix absorbing water during extended contact with the high-moisture RTE chicken breast surface. (iii) Furthermore, the antioxidant efficacy is also lost after day 5 of storage. Further studies should therefore focus on complementary antioxidant analyses to strengthen the oxidative stability profile of developed films. (iv) In addition, protein denaturation analyses would bring valuable mechanistic insights into the shelf life extension potential of the film system for RTE chicken breast. (v) Migration study represents a critical next step for the regulatory validation of this packaging system. Specifically, investigating the diffusion kinetics of RO bioactive compounds using appropriate food simulants would help to establish thresholds for regulatory approval as a food contact material. Future optimization strategies should also address the stability of developed films under high-moisture food storage conditions or alternatively evaluate their applicability in lower-moisture food matrices, where improved functionality and durability may be achieved. (vi) Techno-economic feasibility of the packaging system represents another important parameter in comparison to commercial plastic-based films. The proposed packaging system involved in this study combines biopolymer technology, EO as a clean-label alternative to synthetic preservatives, and nanoencapsulation. Life Cycle Assessment (LCA) can better assess its feasibility and should be considered for future development. Among biopolymers, pectin is a suitable, cost-effective choice because it is produced annually in large quantities from fruit waste, agricultural waste, and food by-products. Pectin production supports the circular economy by reducing waste and pollution (Syarifuddin et al., 2025). RO was incorporated into the pectin matrix to increase its functionality. RO is used as a natural flavoring in the food industry, and it is Generally Recognized as Safe (GRAS) and regulated by the European Food Safety Authority (EFSA) with specific properties (Simić & Ulrih, 2026). Nowadays, traditional extraction methods of RO are being replaced by optimized and enhanced extraction methods, which reduce production costs. Furthermore, because of its volatile nature, nanoencapsulation is required to enhance bioactivity and reduce the amount needed for antimicrobial and antioxidant activity (Yang et al., 2023). Therefore, the lower the RO amount, the lower the cost. Compared to other nanoencapsulation systems, SLN have the benefits of easy, high-scale production at a low cost (Katopodi & Detsi, 2021). Despite the higher cost of the overall production process (materials, technology, formulation, and drying) compared to plastic-based films, the key benefits of the proposed packaging system meet the consumer-driven need for the next generation of food

packaging. Overall, future studies addressing these aspects would support the practical application and potential sustainability advantages of pectin/RO-SLN films for RTE chicken breast.

4. Conclusion

This study evaluated the effects of pectin/RO-SLN films on the microbial, antioxidant, and sensory quality of RTE chicken breast stored under refrigeration conditions (4 ± 1 °C) for 7 days. TSRO and PSRO influenced the properties of pectin films and their efficacy in extending the microbiological, oxidative, and sensory shelf life of RTE chicken breast differently, showing greater effectiveness than CRO. PSRO performed better than TSRO in maintaining the quality of RTE chicken breast, which was attributed to stronger and greater entrapment of RO.

Physical characterization of dried pectin-based films showed improved water-barrier properties in the absence of food contact. Adding RO-SLN decreased moisture content, water solubility, and water vapor permeability by up to 51%, 47%, and 97%, respectively. However, when in direct contact with the surface of RTE chicken breast, the pectin/RO-SLN films swelled and adsorbed water, resulting in weight loss of up to 13% and loss of film integrity. Except for CRO, the initial pH (6.15) remained stable until the end of storage ($p > 0.05$). Wrapped RTE chicken breast with pectin/RO-SLN films showed strong control of microbial growth, with PSRO maintaining $3.63 \pm 0.03 \log_{10}$ CFU/g at day 7, compared with CS, which exceeded the limit of acceptance at $6.61 \pm 0.04 \log_{10}$ CFU/g. Pectin/RO-SLN films slowed lipid oxidation until day 5 of storage. TSRO and PSRO maintained MDA values lower than 0.5 mg/kg on day 5 of storage and exceeded the limit of acceptance (1.0 mg/kg MDA) on day 7. Encapsulation of RO in SLN and the type of SLN emulsifier directly influenced the quality of RTE chicken breast during storage. Before storage, CS had the highest sensory score compared to all wrapped samples. By day 7, PSRO maintained all sensory attributes in an acceptable range (>5), whereas the other samples showed unacceptable scores for smell (CS) and juiciness (CS, CRO, TSRO). In conclusion, the proposed pectin/RO-SLN films represent a promising clean-label packaging system for preserving RTE chicken breast, with potential sustainability advantages as a packaging alternative.

Ethics approval

The Bioethics Committee of the University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, Romania approved the study (No. 567/09.06.2026).

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CRedit authorship contribution statement

Mihaela Stefana Pascuta: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Visualization. **Sonia-Ancuta Socaci:** Methodology, Investigation, Formal analysis, Writing – original draft. **Loredana Leopold:** Methodology, Investigation, Formal analysis. **Maria Ioana Socaciu:** Resources, Methodology. **Cristina Anamaria Semeniuc:** Resources, Methodology. **Elemer Simon:** Writing – original draft, Methodology, Investigation. **Ulrike Sabine van der Schaaf:** Resources, Writing – review & editing. **Dan Cristian Vodnar:** Writing – review & editing, Validation, Supervision, Resources, Visualization, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT-5.6 in order to enhance the clarity and overall quality of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors have no interest to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foohum.2026.101528](https://doi.org/10.1016/j.foohum.2026.101528).

Data availability

Data will be made available upon reasonable request.

References

- Abdollahi, M., Rezaei, M., & Farzi, G. (2012). A novel active bionanocomposite film incorporating rosemary essential oil and nanoclay into chitosan. *Journal of Food Engineering*, 111(2), 343–350. <https://doi.org/10.1016/j.jfoodeng.2012.02.012>
- Abdullah, F. A., Dordevic, D., & Kabourkova, E. (2024). Oxidation status and antioxidant activity of analogue meat products in modified atmosphere packaging. *Applied Sciences*, 14(15).
- Ainani, A. F., Darmawan, Hatimah, H., Hidayat, S. H., Dirpan, A., Majumder, S., & Habiba, W. N. (2026). Pectin-essential oil composite films for active food packaging: A comprehensive review. *Applied Food Research*, 6(1), Article 101652. <https://doi.org/10.1016/j.afres.2025.101652>
- Alemneh, Y., Dalmadi, I., & Kenesei, G. (2025). Effect of refrigeration and frozen storage of raw chicken breast and pork on the quality of sous-vide cooked products. *Progress in Agricultural Engineering Sciences*, 21(1), 443–459. <https://doi.org/10.1556/446.2025.00253>
- Assefi, M., Ataeinaeini, M., Nazari, A., Gholipour, A., Vertiz-Osores, J. J., Melody Calla-Vásquez, K., Zuhair Talib Al-Naqeeb, B., Hussein Jassim, K., Kalajahi, H. G., Yasamineh, S., & Dadashpour, M. (2023). A state-of-the-art review on solid lipid nanoparticles as a nanovaccines delivery system. *Journal of Drug Delivery Science and Technology*, 86, Article 104623. <https://doi.org/10.1016/j.jddst.2023.104623>
- Attallah, O. A., Shetta, A., Elshishiny, F., & Mamdouh, W. (2020). Essential oil loaded pectin/chitosan nanoparticles preparation and optimization via Box–Behnken design against MCF-7 breast cancer cell lines [10.1039/C9RA10204C]. *RSC Advances*, 10(15), 8703–8708. <https://doi.org/10.1039/C9RA10204C>
- Bae, S. M., Cho, M. G., & Jeong, J. Y. (2020). Presalting condition effects on the development of pink color in cooked ground chicken breasts. *Food Science of Animal Resources*, 40(2), 197–208. <https://doi.org/10.5851/kosfa.2020.e4>
- Bertolín, J. R., Joy, M., & Blanco, M. (2019). Malondialdehyde determination in raw and processed meat products by UPLC-DAD and UPLC-FLD. *Food Chemistry*, 298, Article 125009. <https://doi.org/10.1016/j.foodchem.2019.125009>
- Chetia, M. P., Ashraf, G. J., Sahu, R., Nandi, G., Karunakaran, G., Paul, P., & Dua, T. K. (2025). Rosemary (*Rosmarinus officinalis* L.) essential oil: A review of extraction technologies, and biological activities. *Next Research*, 2(3), Article 100545. <https://doi.org/10.1016/j.nexres.2025.100545>
- da Silva, D. J., de Oliveira, M. M., Wang, S. H., Carastan, D. J., & Rosa, D. S. (2022). Designing antimicrobial polypropylene films with grape pomace extract for food packaging. *Food Packaging and Shelf Life*, 34, Article 100929. <https://doi.org/10.1016/j.fpsl.2022.100929>
- Emiroğlu, Z. K., Yemiş, G. P., Coşkun, B. K., & Candoğan, K. (2010). Antimicrobial activity of soy edible films incorporated with thyme and oregano essential oils on fresh ground beef patties. *Meat Science*, 86(2), 283–288. <https://doi.org/10.1016/j.meatsci.2010.04.016>
- Fincheira, P., Espinoza, J., Levio-Raiman, M., Vera, J., Tortella, G., Brito, A. M. M., Seabra, A. B., Diez, M. C., Quiroz, A., & Rubilar, O. (2024). Formulation of essential

- oils-loaded solid lipid nanoparticles-based chitosan/PVA hydrogels to control the growth of *Botrytis cinerea* and *Penicillium expansum*. *International Journal of Biological Macromolecules*, 270(Pt 1), Article 132218. <https://doi.org/10.1016/j.ijbiomac.2024.132218>
- Health Protection Agency.(2009). Guidelines for assessing the microbiological safety of ready-to-eat foods placed on the market. Retrieved from <https://assets.publishing.service.gov.uk/media/66debd72e87ad2f1218265e1/UKHSA-ready-to-eat-guidelines-2024.pdf>. Accessed March 12, 2026.
- Hematizad, I., Khanjari, A., Basti, A. A., Karabagias, I. K., Noori, N., Ghadami, F., Gholami, F., & Teimourifard, R. (2021). vitro antibacterial activity of gelatin-nanochitosan films incorporated with *Zataria multiflora* Boiss essential oil and its influence on microbial, chemical, and sensorial properties of chicken breast meat during refrigerated storage. *Food Packaging and Shelf Life*, 30, Article 100751. <https://doi.org/10.1016/j.foodpack.2021.100751>
- Hong, S.-I., Wang, L.-F., & Rhim, J.-W. (2022). Preparation and characterization of nanoclays-incorporated polyethylene/thermoplastic starch composite films with antimicrobial activity. *Food Packaging and Shelf Life*, 31, Article 100784. <https://doi.org/10.1016/j.foodpack.2021.100784>
- Huang, S., Zhang, Y., Chen, Q., Liu, Y., Lu, L., Arain, M. M., Li, Z., Pan, S., & Liu, F. (2025). Pectin based gels and their advanced application in food: From hydrogel to emulsion gel. *Food Hydrocolloids*, 160, Article 110841. <https://doi.org/10.1016/j.foodhyd.2024.110841>
- Kashiri, M. (2025). Effect of citral incorporation on the antimicrobial, barrier, mechanical, and UV-protective properties of pectin-beeswax films for food packaging applications. *Applied Food Research*, 5(2), Article 101051. <https://doi.org/10.1016/j.afres.2025.101051>
- Katopodi, A., & Detsi, A. (2021). Solid Lipid Nanoparticles and Nanostructured Lipid Carriers of natural products as promising systems for their bioactivity enhancement: The case of essential oils and flavonoids. <https://doi.org/ARTN127529> *Colloids and Surfaces A-Physicochemical and Engineering Aspects*, 630, Article 127529. <https://doi.org/10.1016/j.colsurfa.2021.127529>
- Lacatusu, I., Badea, N., Murariu, A., Nichita, C., Bojin, D., & Meghea, A. (2010). Antioxidant capacity of lipid nanoparticles loaded with rosemary extract, 260/[832]-272/[844] *Molecular Crystals and Liquid Crystals*, 523(1). <https://doi.org/10.1080/15421401003719886>
- Li, Z., Jiang, X., Huang, H., Liu, A., Liu, H., Abid, N., & Ming, L. (2022). Chitosan/zein films incorporated with essential oil nanoparticles and nanoemulsions: Similarities and differences. *International Journal of Biological Macromolecules*, 208, 983–994. <https://doi.org/10.1016/j.ijbiomac.2022.03.200>
- Li, X.-L., Shen, Y., Hu, F., Zhang, X.-X., Thakur, K., Rengasamy, K. R. R., Khan, M. R., Busquets, R., & Wei, Z.-J. (2023). Fortification of polysaccharide-based packaging films and coatings with essential oils: A review of their preparation and use in meat preservation. *International Journal of Biological Macromolecules*, 242, Article 124767. <https://doi.org/10.1016/j.ijbiomac.2023.124767>
- Maćzka, W., Duda-Madej, A., Górny, A., Grabarczyk, M., & Wińska, K. (2021). Can Eucalyptol replace antibiotics? *Molecules*, 26(16), 4933.
- Martău, G. A., Mihai, M., & Vodnar, D. C. (2019). The use of Chitosan, alginate, and pectin in the biomedical and food sector—biocompatibility, bioadhesiveness, and biodegradability. *Polymers*, 11(11).
- Marzlan, A. A., Muhiaddin, B. J., Zainal Abedin, N. H., Manshoor, N., Ranjith, F. H., Anzian, A., & Meor Hussin, A. S. (2022). Incorporating torch ginger (*Etlingera elatior* Jack) inflorescence essential oil onto starch-based edible film towards sustainable active packaging for chicken meat. *Industrial Crops and Products*, 184, Article 115058. <https://doi.org/10.1016/j.indcrop.2022.115058>
- Mehnert, W., & Mäder, K. (2012). Solid lipid nanoparticles: Production, characterization and applications. *Advanced Drug Delivery Reviews*, 64, 83–101. <https://doi.org/10.1016/j.addr.2012.09.021>
- Merenkova, S., & Zinina, O. (2024). Effect of bioactive packaging materials based on sodium alginate and protein hydrolysates on the quality and safety of refrigerated chicken meat. *Polymers*, 16(23), 3430.
- Mohamed, J. M., Alqahtani, A., Ahmad, F., Krishnaraju, V., & Kalpana, K. (2021). Pectin co-functionalized dual layered solid lipid nanoparticle made by soluble curcumin for the targeted potential treatment of colorectal cancer. *Carbohydrate Polymers*, 252, Article 117180. <https://doi.org/10.1016/j.carbpol.2020.117180>
- Mohsenabadi, N., Rajaei, A., Tabatabaei, M., & Mohsenifar, A. (2018). Physical and antimicrobial properties of starch-carboxy methyl cellulose film containing rosemary essential oils encapsulated in chitosan nanogel. *International Journal of Biological Macromolecules*, 112, 148–155. <https://doi.org/10.1016/j.ijbiomac.2018.01.034>
- Montenegro, L., Pasquinucci, L., Zappalà, A., Chiechio, S., Turnaturi, R., & Parenti, C. (2017). Rosemary essential oil-loaded lipid nanoparticles: in vivo topical activity from gel vehicles. *Pharmaceutics*, 9(4), 48.
- Moradi, E., Moosavi, M. H., Hosseini, S. M., Mirmoghtadaie, L., Moslehshad, M., Khani, M. R., Jannatyha, N., & Shojaei-Aliabadi, S. (2020). Prolonging shelf life of chicken breast fillets by using plasma-improved chitosan/low density polyethylene bilayer film containing summer savory essential oil. *International Journal of Biological Macromolecules*, 156, 321–328. <https://doi.org/10.1016/j.ijbiomac.2020.03.226>
- Nikmaran, N., Budaraju, S., Barba, F. J., Lorenzo, J. M., Cox, R. B., Mallikarjunan, K., & Roohinejad, S. (2018). Application of plant extracts to improve the shelf-life, nutritional and health-related properties of ready-to-eat meat products. *Meat Science*, 145, 245–255. <https://doi.org/10.1016/j.meatsci.2018.06.031>
- Nisar, T., Wang, Z. C., Yang, X., Tian, Y., Iqbal, M., & Guo, Y. (2018). Characterization of citrus pectin films integrated with clove bud essential oil: Physical, thermal, barrier, antioxidant and antibacterial properties. *International Journal of Biological Macromolecules*, 106, 670–680. <https://doi.org/10.1016/j.ijbiomac.2017.08.068>
- Pascuta, M. S., & Vodnar, D. C. (2022). Nanocarriers for sustainable active packaging: An overview during and post COVID-19. *Coatings*, 12(1).
- Pascuta, M. S., Wiedenmann, V., Vodnar, D. C., & van der Schaaf, U. S. (2026). Modulation of pectin film properties via various solid lipid nanoparticles formulations: Water barrier and mechanical insights. *Polymers for Advanced Technologies*, 37(6), Article e70649. <https://doi.org/10.1002/pat.70649>
- Penhasi, A., & Meidan, V. M. (2014). Preparation and characterization of in situ ionic cross-linked pectin films: Unique biodegradable polymers. *Carbohydrate Polymers*, 102, 254–260. <https://doi.org/10.1016/j.carbpol.2013.11.042>
- Pintado, T., & Cofrades, S. (2020). Quality characteristics of healthy dry fermented sausages formulated with a mixture of olive and chia oil structured in oleogel or emulsion gel as animal fat replacer. *Foods*, 9(6).
- Prajapati, D., Kelkar, S., Parekh, S., & Prajapati, R. (2026). Lipid-based nanoplateforms for antimicrobial bioactives: Formulation strategies and therapeutic applications. *Next Materials*, 13, Article 103289. <https://doi.org/10.1016/j.nxm.2026.103289>
- Reitznerová, A., Šuleková, M., Nagy, J., Marcincák, S., Semjon, B., Čertík, M., & Klempová, T. (2017). Lipid peroxidation process in meat and meat products: A comparison study of malondialdehyde determination between modified 2-thiobarbituric acid spectrophotometric method and reverse-phase high-performance liquid chromatography. *Molecules*, 22(11).
- Rocha, T. C. d., Costa Filho, D. V., Carvalho, L. M. d., Carvalho, J. M. d., Estévez, M., & Madruga, M. S. (2022). Effect of refrigeration and freezing on the oxidative stability of WB chicken breast. *LWT*, 171, Article 114108. <https://doi.org/10.1016/j.lwt.2022.114108>
- Saber, B., Chockchaisawasdee, S., Golding, J. B., Scarlett, C. J., & Stathopoulos, C. E. (2017). Development of biocomposite films incorporated with different amounts of shellac, emulsifier, and surfactant. *Food Hydrocolloids*, 72, 174–184. <https://doi.org/10.1016/j.foodhyd.2017.05.042>
- Safaeian Laein, S., Khanzadi, S., Hashemi, M., Gheybi, F., & Azizzadeh, M. (2024a). Improving quality of trout fillet using gelatin coating-contain peppermint essential oil loaded solid lipid nanoparticles (PEO-SLN). *Journal of Food Measurement and Characterization*, 18(1), 345–356. <https://doi.org/10.1007/s11694-023-02157-3>
- Safaeian Laein, S., Mohajer, F., Khanzadi, A., Gheybi, F., Azizzadeh, M., Noori, S. M. A., Mollaei, F., & Hashemi, M. (2024b). Effect of alginate coating activated by solid lipid nanoparticles containing *Zataria multiflora* essential oil on chicken fillet's preservation. *Food Chemistry*, 446, Article 138816. <https://doi.org/10.1016/j.foodchem.2024.138816>
- Safaeian Laein, S., Mohajer, F., Khanzadi, A., Gheybi, F., Azizzadeh, M., Noori, S. M. A., Mollaei, F., & Hashemi, M. (2024c). Effect of alginate coating activated by solid lipid nanoparticles containing *Zataria multiflora* essential oil on chicken fillet's preservation. *Food Chemistry*, 446, Article 138816. <https://doi.org/10.1016/j.foodchem.2024.138816>
- Saporito, F., S. G., Bonferoni, M. C., Rossi, S., Boselli, C., Icaro Cornaglia, A., Mannucci, B., Grisoli, P., Viganì, B., & Ferrari, F. (2018). Essential oil-loaded lipid nanoparticles for wound healing. *International Journal of Nanomedicine*, 13, 175–186. <https://doi.org/10.2147/IJN.S152529>
- Selin, C., Tanislav, A., Stan, L., Teleky, B.-E., Ciont, C., Ranga, F., Mureşan, V., Mureşan, A., Vodnar, D. C., Mihai, M., Morariu, I. D., & Pop, O. L. (2025). Exploring the phytochemical and physical stability of phycoyanin, anthocyanins, and betacyanin in a cheese cake product. *Molecular Nutrition & Food Research*, 69(21), Article e70191. <https://doi.org/10.1002/mnfr.70191>
- Shahrampour, D., & Razavi, S. M. A. (2023). Novel antimicrobial/antioxidant *Eremurus luteus* root gum coating containing rosemary essential oil nanoemulsions for extension of chicken meat shelf life. *Food Science & Nutrition*, 11(6), 3131–3140. <https://doi.org/10.1002/fsn3.3295>
- Simić, P., & Uliř, N. P. (2026). Rosemary essential oil as a natural additive in food industry: Recent developments in encapsulation techniques. *Foods*, 15(5), 893.
- Socaciu, M.-I., Fogarasi, M., Semeniciu, C. A., Socaci, S. A., Rotar, M. A., Mureşan, V., Pop, O. L., & Vodnar, D. C. (2020). Formulation and characterization of antimicrobial edible films based on whey protein isolate and tarragon essential oil. *Polymers*, 12(8).
- Socaciu, M.-I., Fogarasi, M., Simon, E. L., Semeniciu, C. A., Socaci, S. A., Podar, A. S., & Vodnar, D. C. (2021). Effects of whey protein isolate-based film incorporated with tarragon essential oil on the quality and shelf-life of refrigerated brook trout. *Foods*, 10(2).
- Stojanović-Radić, Z., Pejić, M., Joković, N., Jakanović, M., Ivić, M., Šojić, B., Škaljac, S., Stojanović, P., & Mihajlov-Krsteš, T. (2018). Inhibition of *Salmonella* Enteritidis growth and storage stability in chicken meat treated with basil and rosemary essential oils alone or in combination. *Food Control*, 90, 332–343. <https://doi.org/10.1016/j.foodcont.2018.03.013>
- Syarifuddin, A., Muflih, M. H., Izzah, N., Fadillah, U., Ainani, A. F., & Dirpan, A. (2025). Pectin-based edible films and coatings: From extraction to application on food packaging towards circular economy- A review. *Carbohydrate Polymer Technologies and Applications*, 9, Article 100680. <https://doi.org/10.1016/j.carpta.2025.100680>
- Teleky, B.-E., Mitrea, L., Plamada, D., Nemes, S. A., Călinoiu, L.-F., Pascuta, M. S., Varvara, R.-A., Szabo, K., Vajda, P., Szekely, C., Martău, G.-A., Elemer, S., Ranga, F., & Vodnar, D.-C. (2022). Development of pectin and poly(vinyl alcohol)-based active packaging enriched with itaconic acid and apple pomace-derived. *Antioxidants*, 11(9).
- Vakili-Ghartavol, M., Arouiee, H., Golmohammadzadeh, S., Naseri, M., & Bandian, L. (2024). Edible coatings based on solid lipid nanoparticles containing essential oil to improve antimicrobial activity, shelf-life, and quality of strawberries. *Journal of Stored Products Research*, 106, Article 102262. <https://doi.org/10.1016/j.jspr.2024.102262>
- Wang, W., Peng, Y., Chen, W., Adie, K., Liu, D., & Yin, Y. (2021). Citrus pectin modified by microfluidization and ultrasonication: Improved emulsifying and encapsulation properties. *Ultrasonics Sonochemistry*, 70, Article 105322. <https://doi.org/10.1016/j.ultsonch.2020.105322>

- Wang, T., Xue, J., Hu, Q., Zhou, M., & Luo, Y. (2017). Preparation of lipid nanoparticles with high loading capacity and exceptional gastrointestinal stability for potential oral delivery applications. *Journal of Colloid and Interface Science*, 507, 119–130. <https://doi.org/10.1016/j.jcis.2017.07.090>
- Wiedenmann, V., Oehlke, K., van der Schaaf, U., Koivula, H. M., Mikkonen, K. S., & Karbstein, H. P. (2019). Emulsifier composition of solid lipid nanoparticles (SLN) affects mechanical and barrier properties of SLN-PROTEIN COMPOSITE FILMS [https://doi.org/10.1111/1750-3841.14950]. *Journal of Food Science*, 84(12), 3642–3652. <https://doi.org/10.1111/1750-3841.14950>
- Wiedenmann, V., Oehlke, K., van der Schaaf, U., Koivula, H. M., Mikkonen, K. S., & Karbstein, H. P. (2019). Emulsifier Composition of Solid Lipid Nanoparticles (SLN) Affects Mechanical and Barrier Properties of SLN-Protein Composite Films. *Journal of Food Science*, 84(12), 3642–3652. <https://doi.org/10.1111/1750-3841.14950>
- WiseGuyReports. (2026, August 2026). *Global Ready to Eat Chicken Breast Market Research Report: size, share & forecast to 2026-2035*. Wise Guy Reports. Retrieved 09.09.2026 from <https://www.wiseguyreports.com/reports/ready-to-eat-chicken-br-east-market>.
- Xie, J., Zhang, Y., Klomklao, S., & Simpson, B. K. (2023). Pectin from plantain peels: Green recovery for transformation into reinforced packaging films. *Waste Manag.* 161, 225–233. <https://doi.org/10.1016/j.wasman.2023.02.035>
- Xie, J., Zhang, Y., Klomklao, S., & Simpson, B. K. (2023). Pectin from plantain peels: Green recovery for transformation into reinforced packaging films. *Waste Management*, 161, 225–233. <https://doi.org/10.1016/j.wasman.2023.02.035>
- Xu, Y., Rehmani, N., Alsabaie, L., Kim, C., Sismour, E., & Scales, A. (2018). Tapioca starch active nanocomposite films and their antimicrobial effectiveness on ready-to-eat chicken meat. *Food Packaging and Shelf Life*, 16, 86–91. <https://doi.org/10.1016/j.fpsl.2018.02.006>
- Yang, J., Goksen, G., & Zhang, W. (2023). Rosemary essential oil: Chemical and biological properties, with emphasis on its delivery systems for food preservation. *Food Control*, 154, Article 110003. <https://doi.org/10.1016/j.foodcont.2023.110003>
- Yu, Y., Gong, M., Wang, S., Wang, X., Liu, Y., Huang, D., Guan, H., Liu, H., Chen, Y., Jiang, Y., & Li, D. (2024). Pectin-based cinnamon essential oil Pickering emulsion film with two-sided differential wettability: A major role in the spatial distribution of microdroplets. *International Journal of Biological Macromolecules*, 277, Article 133727. <https://doi.org/10.1016/j.ijbiomac.2024.133727>
- Zhang, S. K., He, Z. Y., Xu, F. Z., Cheng, Y., Waterhouse, G. I. N., Dongxiao, S. W., & Wu, P. (2022). Enhancing the performance of konjac glucomannan films through incorporating zein-pectin nanoparticle-stabilized oregano essential oil Pickering emulsions (vol 124, 107222, 2022). <https://doi.org/ARTN 107724> *Food Hydrocolloids*, 130, Article 107222. <https://doi.org/10.1016/j.foodhyd.2021.107222>.