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ORIGINAL PAPER

Valorization of oleaster seed by-products as functional edible coatings: Impact on oxidation kinetics modeling of frying oil and quality attributes of fried mussels

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Abstract

Deep-fat frying of seafood often leads to excessive oil uptake and rapid lipid oxidation, compromising both nutritional value and consumer safety. While agri-food by-products are gaining interest as functional ingredients, the potential of oleaster (*Elaeagnus angustifolia* L.) seeds as a naturally gluten-free component in edible coatings remains largely unexplored. This study investigated the effectiveness of oleaster seed flour (OSF)-incorporated coatings on mussels fried at 150, 170, and 190 °C using a multi-analytical approach. Infrared thermography confirmed that the OSF matrix functions as a thermal regulator, ensuring synchronized heat penetration and preventing localized overheating of the delicate mussel tissue. The highest cooking yield and optimal textural integrity were achieved at 170 °C, a temperature that balances rapid crust stabilization with internal moisture retention; whereas at 190 °C, the intense moisture loss was found to create a microporous structure that facilitated increased oil infiltration. Kinetic analysis of the frying oil revealed an activation energy (E_a) of 53.946 kJ/mol and a Q_{10} value of 1.39, demonstrating the high thermal stability of the OSF-coated system against oxidative degradation. Although higher temperatures accelerated Maillard browning, the 150 °C treatment preserved a superior chromatic profile and received the highest sensory scores for aroma and taste. These findings suggest that OSF serves as an effective bioactive carrier and mass-transfer barrier, providing a triple benefit: upcycling agri-food waste, offering a safe alternative for gluten-sensitive populations, and enhancing the oxidative stability of fried seafood systems.

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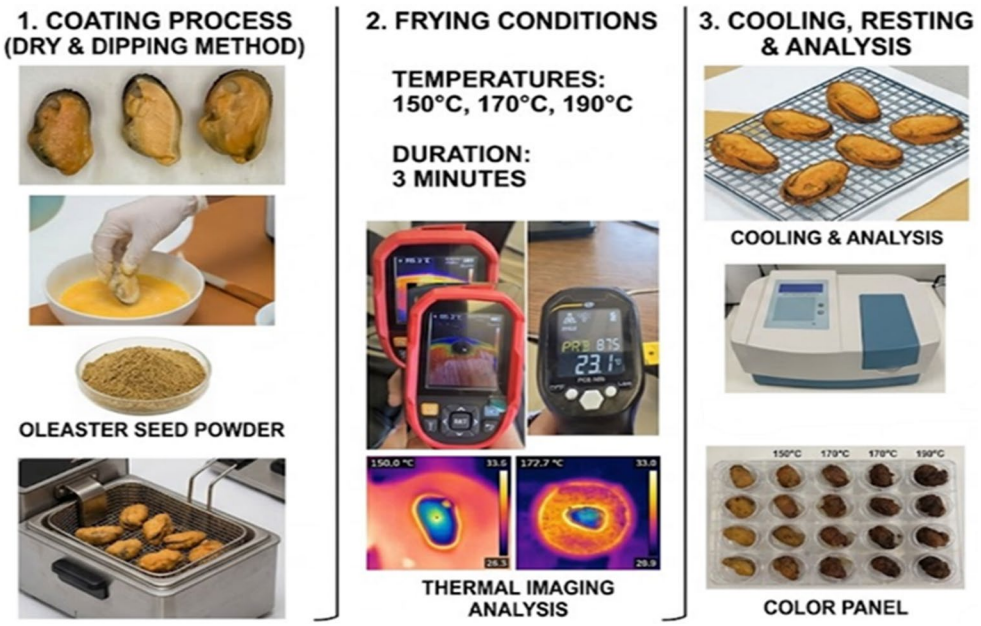
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Graphical abstract



Keywords Oleaster seed flour · Mussel · Agri-food waste valorization · Gluten-free coating · Oxidation kinetics · Thermal imaging

Introduction

Deep-fat frying remains one of the most popular food processing techniques globally due to its ability to create unique sensory attributes, including a crispy texture and desirable golden-brown color [1–3]. However, during the frying process, the frying medium is subjected to high temperatures in the presence of air and moisture, leading to complex chemical reactions such as thermoxidation, polymerization, and hydrolysis which are highly influenced by the food matrix and frying temperature [4, 5]. These reactions result in the formation of polar compounds and primary/secondary oxidation products, such as hydroperoxides and aldehydes, which not only degrade the oil's quality but also pose potential health risks to consumers [6, 7]. Therefore, maintaining the oxidative stability of the frying medium is a critical challenge for the food industry.

Seafood, particularly mussels (*Mytilus chilensis*), is highly valued for its high protein content and rich profile of polyunsaturated fatty acids (PUFAs) [8]. Despite their nutritional benefits, mussels are extremely perishable and susceptible to rapid lipid oxidation and microbiological spoilage during thermal processing [9, 10]. In deep-fat frying, the delicate structure of mussel meat often leads to excessive moisture loss and high oil absorption, which adversely affects both the textural integrity and the nutritional value of the final product [11, 12]. To mitigate these challenges, the application of functional edible coatings has emerged as an effective strategy to create a protective barrier between the food matrix and the frying medium [13–15]. These coatings function by reducing mass transfer specifically by limiting oil uptake and preserving internal moisture [16, 17] while simultaneously acting as a carrier for natural bioactive compounds that can inhibit lipid oxidation, thereby managing the extent of heat-induced structural deformation [18]. In recent years, the rapid expansion of the global gluten-free market, driven by the increasing prevalence of celiac disease and growing health-conscious consumer trends, has created a significant demand for gluten-free coating alternatives in the seafood industry [19–22]. Traditional breading or coating systems often rely on wheat-based ingredients; however, utilizing naturally gluten-free matrices offers a safer and more inclusive functional food option without compromising the product's quality. Recently, there has been a growing interest in "upcycling" agri-food by-products into these coating formulations to support a circular economy and enhance food sustainability [23–25].

Oleaster (*Elaeagnus angustifolia L.*) seeds, often discarded as waste during the processing of oleaster fruits, represent a potent source of bioactive compounds, including phenolic acids, flavonoids, and functional fibers [26, 27]. While the antioxidant properties of oleaster fruit pulp are well-documented, the potential of its seeds as a functional, naturally gluten-free ingredient in edible coatings remains largely unexplored. Utilizing oleaster seed flour (OSF) in

mussel coatings could provide a triple benefit: stabilizing the frying oil against thermal degradation, protecting the mussel meat from oxidation, and providing a high-quality gluten-free alternative for sensitive consumer groups. This study aims to evaluate the effectiveness of oleaster seed flour-incorporated coatings on the quality attributes of mussels fried at three different temperatures. A comprehensive kinetic approach was employed to characterize the degradation of the frying oil and the quality evolution of the mussels. Furthermore, advanced thermal imaging was utilized to visualize heat distribution during frying, providing a deeper understanding of the interaction between the coating and the thermal processing environment. This research provides a novel perspective on the valorization of agri-food waste for the development of sustainable, gluten-free, and functional seafood systems.

Materials and methods

The primary raw material, frozen and shucked mussel meat (*Mytilus chilensis*), was supplied by Balık Dünyası Co. (Türkiye). Oleaster (*Elaeagnus angustifolia L.*) seed powder was provided by Tazemiz Co. (Türkiye). Culinary-grade eggs, sunflower oil, and salt used in the coating formulations were sourced from local suppliers.

Mussel coating and frying process

Frozen mussels were thawed at room temperature and thoroughly washed and cleaned to remove any impurities. The prepared mussel meat was initially dipped in a beaten egg solution and then uniformly coated with oleaster seed powder. The frying process was performed in a temperature-controlled deep fryer (Tefal, Türkiye) at three different temperatures (150, 170, and 190 °C) for a constant duration of 3 min. Following the frying stage, the samples were allowed to rest for 20 min at ambient temperature to reach equilibrium before being subjected to further analytical procedures.

Determination of coating efficiency and cooking yield

The coating efficiency and cooking yield of the mussel samples were determined gravimetrically according to the method described by Bhuiyan and Ngadi [28], with slight modifications. The weights of the mussels were recorded at three critical stages: raw (W_{raw}), coated (W_{coated}), and fried (W_{fried}).

The Coating Efficiency (CE), representing the amount of coating material adhered to the mussel surface, was calculated using the following equation:

$$CE\,(\%)\,\frac{W_{coated}-W_{raw}}{W_{raw}}x100$$

The Cooking Yield (CY), which indicates the weight retention of the samples after thermal treatment at different frying temperatures (150, 170, and 190 °C), was determined as follows:

$$CY\,(\%)=\frac{W_{fried}}{W_{coated}}x100$$

The Total Process Yield (TYP) was calculated to evaluate the overall weight change from the initial raw state to the final fried product, encompassing both the coating adhesion and the mass transfer during frying. It was determined using the following equation:

$$TYP\,(\%)=\frac{W_{fried}}{W_{raw}}x100$$

All measurements were performed in triplicate for each temperature group, and the results were expressed as mean percentages ± standard deviation.

Color properties

The surface color of the coated mussels was determined using a Konica Minolta Chroma Meter (Konica Minolta Sensing Inc., Osaka, Japan) before and after the frying process. Color coordinates were recorded as L^*, a^*, and b^* [29]. For each frying treatment, 5 independent samples were analyzed. Color measurements were performed after removing excess surface oil from the samples and allowing them to cool at room temperature (25 °C) for 15 min following frying. To quantify the overall color transformation induced by the oleaster seed powder coating across different frying temperatures, the total color difference (ΔE*) was determined relative to the pre-frying stage. The calculation was performed according to the established methodology using the following equation:

$$\Delta E^*$$
$$\sqrt{\left(L^*_{sample}-L^*_{control}\right)+\left(a^*_{sample}-a^*_{control}\right)^2+\left(b^*_{sample}-b^*_{control}\right)^2}$$

Thermal profiling and surface temperature analysis during frying

The surface and internal temperature profiles of the mussel samples were monitored throughout the frying process. Initial and surface temperatures were recorded at 1-minute intervals using a thermal imaging camera (Uni-T, UTi120S) and an infrared thermometer (PCE-895, PCE Instruments). To determine the effect of the olive seed powder-based coating on temperature distribution under various frying conditions (150, 170, and 190 °C), all thermal data were collected in triplicate [30].

Sensory evaluation

Sensory analysis of the fried mussels was conducted immediately after the 3-minute frying process was completed. Prior to the analysis, the experimental procedure was reviewed and approved by the Social Sciences Scientific Research Proposal Ethics Evaluation Committee of Sivas Cumhuriyet University (Decision Date: March 12, 2026; Decision No: 31).

Sensory evaluation of the samples was conducted by a panel of 25 trained participants (13 females and 12 males) in accordance with the standard method ISO 4121 [31]. The samples were assessed based on color, taste, aroma, texture, and overall appearance using a structured 9-point hedonic scale, where 1 represented 'dislike extremely', 5 represented 'neither like nor dislike', and 9 represented 'like extremely.

Oxidative stability of frying oil

To assess the changes occurring in sunflower oil during the deep-frying of seabass mussels coated with olaster, the peroxide value (PV) of the oil samples was determined following the AOAC Official Method Cd 8–53 [32]. Free fatty acids (FFA) were quantified according to IUPAC Method 2.201 [33]. Measurement of conjugated dienes (CD) and conjugated trienes (CT) was performed as an indicator of the oxidative stability of the frying oils. Conjugated dienes exhibit absorbance at 232 nm, whereas conjugated trienes absorb at 270 nm. To evaluate the formation of secondary oxidation products, the p-anisidine value (p-AV) was determined. The calculation of p-AV was performed according to the following formula [33]:

$$p - Anisidine\ Value\ (p - AV) = \frac{25 \times\ (1.2 \times\ A2 - A1)}{M}$$

where M represents the mass of the oil sample in grams, A1 is the absorbance measured at 350 nm prior to the addition of p-anisidine, and A2 is the absorbance at 350 nm after the addition of p-anisidine.

Kinetic analysis of peroxide values during frying

To evaluate the kinetics of peroxide value changes, sunflower oil samples obtained from frying mussels coated with oleaster (*Elaeagnus angustifolia*) seed flour at 150, 170, and 190 °C were analyzed. Peroxide values were used as the primary oxidation parameter, and linear regression analysis was performed to determine the reaction kinetics. The changes in oil quality indices were modeled according to zero-order and first-order reaction kinetics [34, 35].

$$Pt = Po \pm kt$$

$$In\ Pt = In\ Po \pm kt$$

where P0: value of the oil quality index at time (t)=0; Pt: value of the oil quality index at a given time (t); k: rate constant.

Regression equations were calculated for each kinetic model, and the models were compared based on their coefficient of determination (R^2) values. The model exhibiting the highest R^2 was considered the most suitable kinetic model for the system, and the corresponding rate constants (k) were determined at the different temperatures.

Activation energy (Ea, kJ mol^{-1}) and the pre-exponential (frequency) factor (A, h^{-1}) were calculated from the slope and intercept of the linear regression obtained by plotting ln(k) versus 1/T according to the Arrhenius relationship. Nevertheless, any deviation from linearity in the ln(k)–1/T plot suggests that the lipid oxidation mechanism may not strictly follow classical Arrhenius behavior, and can instead be described as sub-Arrhenius (positive deviation) or super-Arrhenius (negative deviation) [35].

$$ln\,(k)\ =\ ln\,(A) - (Ea/RT)$$

In this context, k represents the reaction rate constant, A is the frequency factor, Ea denotes the activation energy (kJ mol^{-1}), R is the universal gas constant (8.314 J K^{-1} mol^{-1}), and T is the absolute temperature (K). The Q10 coefficient expresses the change in reaction rate corresponding to a 10 °C increase in temperature [35].

$$Q10\ e^{\frac{Ea\times\ 10}{RT(T+10)}}$$

Furthermore, activation enthalpy (ΔH^{++}) and activation entropy (ΔS^{++}) were determined based on the Activated Complex Theory [35].

$$ln\ (k/T) = ln\ (kB/h)$$
$$1(\triangle S^{++}/R) - (\Delta H^{++}/RT$$

In this context, kB denotes the Boltzmann constant (1.380658×10^{-23} J K^{-1}), while h represents the Planck constant ($6.6260755 \times 10^{-34}$ J·s). The activation enthalpy (ΔH^{++}) and activation entropy (ΔS^{++}) values were obtained from the slope and intercept of the corresponding linear plots. In addition, the Gibbs free energy of activation (ΔG^{++}) was determined using Eq.

$$\triangle G^{++} = \triangle H^{++} - T\triangle S^{++}$$

Statistical analysis

The experimental data were subjected to one-way analysis of variance (ANOVA) to evaluate the effects of different frying temperatures and coating treatments. All measurements were performed in triplicate, and the results were expressed as mean ± standard deviation. Significant differences among the means were determined using Tukey's post hoc test at a confidence level of $p < 0.05$. All statistical procedures were conducted using SPSS Statistics 17.0 software.

Result and discussion

Effect of frying temperature on coating efficiency and cooking yields

The impact of different frying temperatures on the physical properties and yield parameters of the mussel samples is shown in Table 1. For all experimental groups, the coating pick-up was maintained at a constant rate of approximately 26%, ensuring a uniform starting matrix for the thermal treatment.

Regarding cooking yield, a non-linear trend was observed as the frying temperature increased. Interestingly, the highest cooking yield was recorded at 170 °C, whereas the values were significantly lower ($p < 0.05$) at 150 °C and 190 °C. The peak yield at 170 °C suggests an optimal balance, where the OSF coating reaches structural maturity quickly enough to trap internal moisture before excessive evaporation occurs. In contrast, the decline observed at 190 °C can be attributed to accelerated thermal stress and rapid moisture loss. High-temperature frying triggers more aggressive protein denaturation and subsequent fiber shrinkage in mussel tissue. This downward trend is consistent with the findings for other fried matrices, such as poultry and potatoes, where heat-induced volumetric shrinkage is closely linked to rapid moisture evaporation and subsequent weight loss [36, 37]. Research indicates that higher frying temperatures accelerate shrinkage rates, which negatively impact the final yield by increasing porosity and altering the mass transfer dynamics within the product [17, 38]. Although mussels possess a more delicate protein structure than poultry, the fundamental mechanism remains the same: controlling frying conditions is crucial for optimizing cooking yield by managing the extent of heat-induced structural deformation and moisture expulsion [18].

In contrast to the cooking yield, the total process yield showed a significant linear increase with increasing temperature ($p < 0.05$). The total process yield, which was 132.60% at 150 °C, reached a maximum of 162.08% at 190 °C. This phenomenon indicates a shift in the mass transfer dynamics at elevated temperatures; while the core loses more moisture, the OSF-based coating facilitates a more substantial uptake or adsorption of oil on its surface. The rapid formation of a highly porous crust at 190 °C likely created a matrix with an increased oil-holding capacity, significantly augmenting the final weight of the product despite the reduction in internal mussel mass. This mechanism is supported by advanced microstructural observations showing that as frying progresses, water evaporation creates three-dimensional pore networks that serve as primary pathways for oil infiltration [38]. Furthermore, the structural integrity of the crust and its porosity are directly correlated with the final oil content, as oil predominantly occupies the void spaces created during the intense moisture loss phase [16]. This dual behavior highlights that the OSF coating acts as a functional barrier that effectively manages the trade-off

Table 1 Coating pick-up, cooking yield, and total process yield of mussels coated with oleaster powder-based edible coatings at different frying temperatures

Frying Temperature °C	Coating Pick-up (%)	Cooking Yield (%)	Total Process Yield (%)
150	26 ± 0.03	124.50 ± 0.59^{a}	132.60 ± 1.15^{c}
170		122.48 ± 0.91^{b}	153.05 ± 2.01^{b}
190		118.97 ± 0.67^{c}	162.08 ± 3.08^{a}

Values are expressed as mean ± standard deviation. Different superscript letters (a-c) in the same column indicate statistically significant differences ($p < 0.05$)

between moisture retention and oil interaction, with 170 °C emerging as the most favorable temperature for maintaining the internal 'juiciness' (cooking yield) of the mussels.

Color properties

The effects of different frying temperatures on the surface color parameters (L^*, a^*, and b^*) of mussels coated with oleaster powder-based edible coatings are presented in Table 2. Statistical analysis revealed that both the frying process and the incremental increase in frying temperature significantly influenced the color profile of the samples ($p < 0.05$). A sharp decrease was observed in the L^* values, which dropped from an initial 68.15 in the pre-frying samples to as low as 10.95 at 190 °C. This darkening of the crust is a hallmark of the advanced stages of the Maillard reaction and caramelization, both of which are accelerated by high thermal energy [39–41].

Similarly, the b^* (yellowness) values showed a significant downward trend, declining from 42.39 to 18.89 as the temperature increased to 190 °C. This reduction in yellowness, particularly at higher temperatures, can be attributed to the thermal degradation of natural pigments within the oleaster powder and the formation of brown melanoidins [43–45].

In contrast, a^* (redness) values showed a significant increase from 14.71 (pre-frying) to approximately 30–31 after frying across all temperature groups. Interestingly, while the redness increased compared to the raw state, the values remained relatively stable between 150 °C and 190 °C, indicating that the development of red hues occurs rapidly even at the lowest frying temperature studied. Overall, the color data suggest that while higher temperatures (190 °C) lead to a significantly darker and less yellow crust, the 150–170 °C range maintains a more balanced chromatic profile, likely reflecting a more controlled non-enzymatic browning process suitable for consumer preference.

Consequently, the total color difference (ΔE^*) values rose significantly from 50.31 to 63.92 ($p < 0.05$), with the most substantial shift occurring at 190 °C. This intense color development can be attributed to the acceleration of Maillard browning and caramelization reactions involving the inherent sugars and proteins within the oleaster seed powder. These findings suggest that while lower temperatures preserve a more golden-yellow hue, higher frying temperatures promote the formation of a dark, characteristic crust, which is a critical quality attribute for consumer perception of fried seafood products.

Thermal imaging

The real-time thermal evolution of oleaster seed flour (OSF)-coated mussels during deep-fat frying at varying temperatures (150, 170, and 190 °C) was characterized using infrared thermography, with the resulting surface and internal temperature profiles illustrated in Fig. 1. Quantifying the temperature gradient between the product surface, monitored via thermography, and its geometric center is essential for elucidating the heat transfer kinetics and thermal barrier efficiency of the applied coating matrix. Heat transfer during deep-fat frying typically initiates through convection from hot oil to the food surface, followed by conduction inward to the core [41, 42]. The presence of a coating layer, such as the OSF-based matrix in this study, can significantly influence these heat transfer coefficients by acting as a regulated insulating layer that modulates the temperature profile within the product [46, 47]. Therefore, monitoring these surface-to-core gradients is critical for assessing thermal evolution and predicting subsequent quality changes, including moisture loss, oil uptake, and textural integrity in coated fried seafood [48].

At the initial stage (0 min), the samples exhibited a uniform temperature distribution ranging from 19.3 °C to 19.7 °C. Upon immersion, a rapid thermal flux was observed in all cohorts within the first minute. In the 150 °C group, the surface temperature escalated to 92.6 °C, whereas the internal temperature reached 80.3 °C, establishing an initial gradient of ~ 12.3 °C. This rapid heat elevation indicates that the OSF-based coating facilitates an efficient initial heat flux, allowing for rapid core heating without functioning as an excessive thermal insulator [44, 49]. While certain hydrocolloid-based coatings, such as xanthan gum, are known to create an insulating layer that significantly lowers heat transfer rates [50], the OSF matrix appears to maintain a favorable balance of thermal conductivity. This characteristic ensures effective heat penetration required for rapid

Table 2 Effect of different frying temperatures on the color parameters of mussels coated with oleaster powder-based edible coatings

Frying Temperature°C	Color Parameters			
	L*	a*	b*	ΔE*
Pre-frying	68.15 ± 0.28^{a}	14.71 ± 0.02^{c}	42.39 ± 0.01^{a}	-
150	21.07 ± 0.05^{b}	31.37 ± 0.04^{a}	36.28 ± 0.03^{b}	50.31
170	19.03 ± 0.03^{c}	30.10 ± 0.07^{b}	32.79 ± 0.04^{c}	52.33
190	10.95 ± 0.04^{d}	30.90 ± 0.04^{ab}	18.89 ± 0.05^{d}	63.92

Values are expressed as mean ± standard deviation. Different superscript letters (a-c) in the same column indicate statistically significant differences ($p < 0.05$)

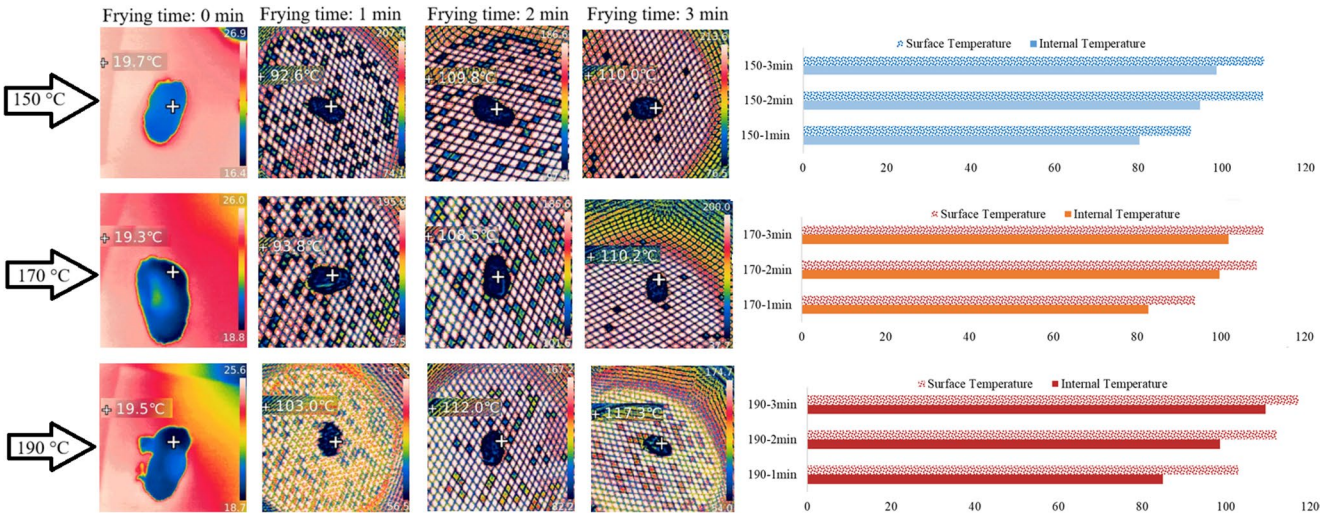


Fig. 1 Real-time thermal evolution of oleaster seed flour (OSF)-coated mussels during deep-fat frying at different temperatures (150, 170, and 190 °C): Infrared thermography images (left) and surface/core temperature profiles (right)

cooking and safety, while potentially functioning as a regulated mass-transfer barrier to mitigate oil uptake and preserve moisture [51].

As the frying duration progressed, a distinct thermal convergence behavior was observed across all experimental conditions, where the gradient between the surface and core temperatures narrowed progressively from the 1st to the 3rd min. In the 170 °C group, the gradient decreased from 11.1 °C to 8.4 °C, whereas at 190 °C, the differential narrowed significantly from 18.1 °C to 7.9 °C. This equilibration process suggests that as the coating undergoes rapid moisture evaporation and subsequent crust stabilization, the OSF matrix establishes a consistent and conductive interface. Although the formation of a porous crust typically increases conductive resistance owing to reduced moisture content [52]), it simultaneously enhances the overall heat transfer efficiency by promoting intense vapor dynamics and convective heat exchange at the surface interface [53, 54]. The release of water vapor bubbles during this stage likely offsets the conductive resistance of the crust, acting as a functional thermal bridge that facilitates a rapid transition towards thermal equilibrium across the product matrix [53–55]. As the crust becomes more stable, it facilitates a more uniform thermal distribution, ensuring synchronized heat penetration and preventing localized overheating [56, 57].

Ultimately, this integration of infrared thermography and simultaneous core temperature measurements confirmed that while the frying media temperature is the primary driving force for the heating rate, the OSF coating functions as a thermal regulator. These findings suggest that the OSF matrix may contribute to preserving the textural and structural integrity of mussels by facilitating more uniform heat penetration .This regulated thermal profile prevents rapid, non-uniform protein denaturation often associated with uncontrolled high-temperature frying, thereby maintaining a favorable balance between the desired degree of doneness and preservation of the delicate quality of seafood tissue.

Sensory evaluation

The effect of frying temperature on the sensory scores of the oleaster flour-coated mussels is shown in Fig. 2. Overall, the highest scores across all sensory parameters (color, aroma, taste, texture, and appearance) were obtained for the samples fried at 150 °C. A linear decrease in sensory preference scores was observed as the temperature increased from 150 to 190 °C, with the 170 °C group yielding intermediate scores across all evaluated parameters (Fig. 2).

Specifically, the color and appearance scores ranged between 7.4 and 8.1 at 150°C but dropped below 6.0 at 190°C. This decline can be attributed to excessive browning caused by the rapid caramelization and Maillard reactions of the sugars present in the oleaster seed powder at higher temperatures [58, 59]. Furthermore, the inherent dark pigmentation of the oleaster seed powder likely contributed to this effect; when combined with high-temperature frying, this natural color intensified, leading to a deeper, 'burnt-like' appearance that was less preferred by the panelists.

For aroma and taste, the 150 °C group received the highest appreciation (8.45 and 7.73, respectively), while the 190 °C group received the lowest scores. This decrease is likely due to the thermal degradation of the characteristic volatile profile of the oleaster seed powder at elevated temperatures. Undesirable flavor compounds, such as aldehydes, ketones, and furans, are formed in fried foods

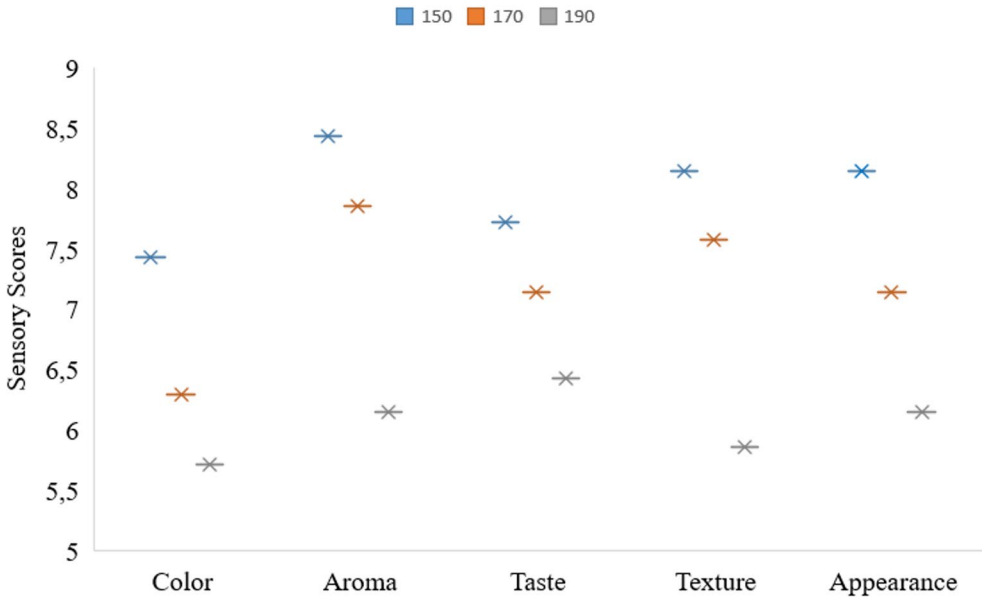


Fig. 2 Sensory profiles and consumer preference scores of OSF-coated mussels fried at various temperatures (150, 170, and 190 °C)

through lipid oxidation and amino acid degradation, leading to rancid or metallic off-flavors [60, 61]. While protein-based coatings can potentially mitigate Maillard reaction products by competing with amino acids [62], the intensity of frying at 190 °C may have triggered the formation of bitter thermal degradation products due to the high sugar and fiber content of the oleaster powder.

The texture scores exhibited a significant decline as the frying temperature increased, decreasing from 8.15 at 150 °C to 5.86 at 190 °C. This deterioration in sensory perception can be attributed to accelerated moisture loss and subsequent hardening of the mussel meat, alongside the over-drying of the coating layer. Elevated frying temperatures are known to significantly affect the texture of seafood by inducing protein denaturation and altering the porous structure, which directly increases hardness while reducing chewiness [63, 64].

In this study, the sharp reduction in moisture content at 190 °C likely correlated with increased hardness, a phenomenon in which moisture depletion adversely affects the sensory quality of fried fish products [65]. Furthermore, over-drying the coating may have influenced its glass transition temperature, affecting post-fry texture stability and resulting in an excessively brittle or hardened crust at the highest temperature [28]. While the optimized conditions (150 °C) balance texture and moisture retention, excessive temperatures cause the sensory quality to deteriorate through severe moisture depletion and coating hardening.

Overall, thermal degradation during frying leads to the formation of both desirable and undesirable flavor compounds in coated foods [60, 62, 66]. While the lower oxidation levels observed could be influenced by the antioxidant properties of the OSF components, it is likely that the coating primarily functions as a physical barrier. By promoting more uniform heat distribution and potentially reducing oil-substrate interaction, the OSF matrix limits the thermal degradation of lipids. Further studies involving direct antioxidant assays on the fried matrix are required to decouple the chemical scavenging effects from the physical protection provided by the coating.

Oxidative stability of frying oil

The oxidative stability of oils can be effectively evaluated using conventional quality parameters, such as the peroxide value, free fatty acid content, K232, K270, and p-anisidine value [67]. The changes in peroxide value, p-anisidine, K232, K270, and free fatty acid content following the frying of oleaster seed flour-coated mussels at 150 °C, 170 °C, and 190 °C are presented in Table 3.

The peroxide value is a key indicator of the accumulation of hydroperoxides formed during the initial stage of lipid oxidation [68]. During frying, free radical chain reactions promote the formation of hydroperoxides, leading to an increase in the peroxide value [69–72]. For high-quality vegetable oils, recommended guidelines generally suggest an initial peroxide value of ≤ 12 meq O_2/kg [73]. The initial peroxide value of sunflower oil was determined as 5.73 meq O_2/kg and the measured value indicates that the oil exceeds the recommended limit for optimal quality. In this study, the peroxide value increased from 8.25 meq O_2/kg at 150 °C to 15.26 meq O_2/kg at 190 °C, indicating that hydroperoxide formation accelerated with increasing frying temperature. This trend suggests a decline in oxidative stability as the temperature increases. The rapid accumulation of hydroperoxides at elevated temperatures highlights

Table 3 Oxidation values of oils used in frying

Peroxide value (meqO2/kg)	150 °C	170 °C	190 °C
	8.25 ± 0.01^{c}	10.80 ± 0.00^{b}	15.26 ± 0.05^{a}
Free fatty acidity	0.19 ± 0.03^{b}	0.23 ± 0.02^{a}	0.25 ± 0.01^{a}
K232	1.7 ± 0.02^{c}	2.05 ± 0.00^{b}	2.60 ± 0.03^{a}
K270	0.2 ± 0.01^{c}	0.8 ± 0.04^{b}	1.2 ± 0.02^{a}
p-anisidin	5.25 ± 0.07^{c}	6.45 ± 0.06^{b}	9.40 ± 0.01^{a}

Values are expressed as mean ± standard deviation. Different superscript letters (a-c) in the same raw indicate statistically significant differences ($p < 0.05$)

the intensification of early stage oxidative degradation processes [69]. Furthermore, prolonged thermal exposure exacerbified oxidative deterioration. For instance, frying at 180 °C for extended periods in sunflower and corn oils has been reported to significantly enhance thermal oxidation, particularly in the presence of food matrices such as potato chips [74]. Elanine et al. [68] reported that, during repeated frying of potatoes in sunflower oil at 180 °C, the peroxide value increased progressively up to the eighth frying cycle.

Free fatty acidity primarily develops during frying as a result of hydrolytic reactions, where moisture released from the coated, high-water-content food promotes the breakdown of triglycerides into free fatty acids and mono- and diacylglycerols. This parameter is widely recognized in the food industry as an important indicator of the quality of frying oil. In addition, the intrinsic components of foods, including proteins, carbohydrates, lipids, and water, actively participate in the complex reactions that occur during frying [75, 76]. In the present study, the free fatty acidity increased from 0.19 to 0.25 in samples fried at 150 °C, 170 °C, and 190 °C. This increase can be attributed to moisture transfer from the oleaster-coated mussels to the frying medium, which enhances triglyceride hydrolysis.

The increase in K232 values from 1.7 to 2.60 indicates an increased formation of conjugated dienes, which are characteristic primary oxidation products. The parallel increase observed between K232 and the peroxide value suggests a strong association between hydroperoxide formation and the development of conjugated double bond systems. Furthermore, increases in the K270 and p-anisidine values, which represent secondary oxidation products, were also observed. The elevation of K270 from 0.2 to 1.2 reflects the decomposition of hydroperoxides into carbonyl compounds. Similarly, the increase in the p-anisidine value from 5.25 to 9.40 indicates the enhanced formation of aldehydic compounds. However, the comparatively moderate increase in p-anisidine relative to the peroxide value suggests that primary oxidation processes remain dominant and that the degradation of hydroperoxides into secondary products has not yet progressed extensively. Moreover, the relatively higher p-anisidine and K270 values observed in oils obtained from frying oleaster-coated mussels support the notion that starch-based coatings can accelerate oxidative deterioration [77]. Deep-fat frying of dough-based products in sunflower oil at temperatures between 160 and 180 ± 5 °C for durations ranging from 30 s to 6 min has been reported to increase p-anisidine values, indicating intensified secondary oxidation reactions [76].

In conclusion, while frying at an elevated temperature of 190 °C naturally increases both primary and secondary oxidation products, the presence of the oleaster seed flour coating may help modulate the overall oxidative degradation of the oil. The structural characteristics and composition of the coating material appear to play significant roles in accelerating oxidative degradation during frying.

Effects of frying temperature on the formation kinetics and thermodynamics parameters of peroxide values

Lipid oxidation is one of the most critical factors affecting oil quality. The determination of the kinetic parameters of lipid oxidation provides valuable insights into oxidative stability, processing suitability, and resistance to elevated temperatures during storage. In this study, the rate constant of peroxide formation (k) was determined using a zero-order kinetics model. It has been reported that oxygen consumption during the stage in which oxygen reacts with free radicals to form peroxide radicals and hydroperoxides follows a zero-order kinetics [78]. The reaction rate constants (k, h^{-1}) for sunflower oils at different frying temperatures are summarized in Table 4. As expected, increasing the frying temperature led to a corresponding rise in k values across all samples, signifying the acceleration of lipid oxidation at elevated temperatures. Similarly, peroxide formation in avocado oil stored at 25, 45, and 65 °C was evaluated to estimate the extent of oxidation reactions, with the rate constant (k) determined using a zero-order kinetic model. Furthermore, Gómez-Alonso et al. [79] investigated the autoxidation of olive oil triacylglycerols in the absence of prooxidants and antioxidants within the temperature range of 25–75 °C under dark conditions and reported that both the peroxide value and UV absorbance at 270 nm were well described by a zero-order kinetic model.

Table 4 Effects of frying temperature on the formation kinetics and thermodynamics parameters of peroxide values

Peroxide value(meq O_2/kg)	150 °C	8.25
	170 °C	10.80
	190 °C	15.26
k values	150 °C	2.52
	170 °C	5.07
	190 °C	9.52
ln (k)	150 °C	0.92
	170 °C	1.62
	190 °C	2.25
ln(k) = ln(A)−(Ea/RT)	Ea (kJ/mol)	53.946
	A × 10^7 (1/h)	1.22
	R^2	0.99
ln (IP) = a(T) + b	Tcoeff.×10^{-2} (K^{-1})	1.53
	Q_{10}	1.39
ln (k/T) = ln (kB/h)1(ΔS^{++} /R)-(ΔH^{++}/RT)	ΔH++ ($kJmol^{-1}$)	50.48
	ΔS++ (J/Kmol)	-185.40
	R^2	0.99
ΔG^{++}=Δ H^{++}- TΔS^{++}	ΔG++(kJmol-1) (383.15)	128.93
	ΔG^{++}($kJmol^{-1}$) (393.15)	132.64
	ΔG^{++}($kJmol^{-1}$) (403.15)	136.35

Activation energy (Ea) is a critical parameter that reflects the resistance of oils to oxidation and the sensitivity of the oxidation rates to temperature [35, 80]. Lower Ea values indicate that the oil is more prone to rapid deterioration, whereas higher values suggest greater resistance to thermal processing [81, 82]. Based on the Arrhenius parameters calculated from the reaction rate constants derived from peroxide value changes, the activation energy was determined to be 53.946 kJ/mol (Table 4). This value clearly demonstrates the temperature dependence of the lipid oxidation. The high correlation coefficient (R^2 = 0.991) confirms that the variation in the reaction rate constants with temperature is in excellent agreement with the Arrhenius model. A relatively high Ea value indicates an increased energy barrier that must be overcome for oxidation to occur [83]. In the literature, the activation energy for lipid oxidation processes typically ranges between 40 and 400 kJ/mol, indicating that the reaction is both chemically active and temperature sensitive [84]. Within the scope of this study, the dehydration of the oleaster coating on the mussel surface during frying can be associated with overcoming this energy barrier. The obtained activation energy of 53.946 kJ/mol suggests that increasing the temperature significantly accelerates the frying process without leading to uncontrolled thermal degradation. Moreover, the relatively high frequency factor (A = 1.13 × 10^7 h^{-1}) indicates a high frequency of effective molecular collisions and a favorable probability of reaction occurrence within the system.

The Tc and Q10 values of sunflower oils obtained from frying oleaster seed flour-coated mussels at different temperatures are presented in Table 4. Tc and Q10 are important kinetic parameters used to evaluate the effect of temperature on lipid oxidation [85]. The Q10 value was determined to be 1.39, indicating that a 10 °C increase in temperature leads to an approximately 39% increase in the oxidation rate. The fact that this value remains below 2.0 suggests that the system exhibits relatively high thermal stability against sudden temperature changes and that oxidative degradation does not accelerate. This stability is further supported by the temperature coefficient (Tcoeff) of 1.535 × 10^{-2} K^{-1}.

The reaction rate was further characterized using transition state parameters derived from the Eyring equation, namely enthalpy (ΔH^{++}), which reflects the energetic requirements of the reaction, and entropy (ΔS^{++}), which represents the degree of disorder and energy distribution within the system. As shown in Table 4, the ΔH^{++} value (50.48 kJ/mol) is consistent with the activation energy, whereas the ΔS^{++} value is negative (− 185.4 J/mol·K). A negative entropy value indicates that the transition state requires a more ordered molecular arrangement [80]. This finding suggests that within the matrix formed by the oleaster coating, molecules participate in the reaction in a more organized manner with limited random diffusion. The activation enthalpy (ΔH^{++}) and activation entropy (ΔS^{++}) values estimated for the lipid oxidation of vegetable oils based on the activated complex theory and corresponding regression parameters are presented in Table 4. The high correlation coefficients (R^2 > 0.99) confirmed the suitability of the activated complex theory in describing the temperature dependence of lipid oxidation. The positive enthalpy change indicates that the reaction is endothermic. Similar findings have been reported in previous studies investigating lipid oxidation in various vegetable oils [82, 85–87].

The sign of the Gibbs free energy change provides insight into whether oxidation reactions occur spontaneously and whether they are exothermic or endothermic processes [35, 88]. The observed increase in Gibbs free energy (ΔG^{++}) values with temperature (128.93–136.35 kJ/mol) indicates a rise in the overall energy barrier required for the reaction to proceed (Table 4). Nevertheless, the concurrent increase in rate constants suggests that the effect of temperature on molecular kinetic energy predominates over the energy barrier. This finding implies that the coating material does not completely inhibit the reaction but significantly retards its progression. Furthermore, the positive Gibbs free energy values obtained for sunflower oil samples indicate that

the oxidation reaction is non-spontaneous and endothermic in nature.

Conclusion

This research demonstrates that oleaster seed flour (OSF) can be successfully utilized as a high-performance functional component to improve the quality of gluten-free fried seafood. The main findings of this study reveal that OSF supplementation significantly improves cooking yield, reduces oil absorption, and noticeably modifies the color profile of the fried product. Furthermore, under the tested frying conditions, the OSF based coating exhibited a distinct impact on oxidative behavior, effectively retarding lipid oxidation. A critical interplay was observed between frying temperature and the structural integrity of the coating. While the OSF matrix shows potential as a thermal regulator to support uniform cooking, the transition to 190 °C marks a threshold where intense moisture loss compromises the coating matrix, creating micro-porous pathways that facilitate oil infiltration. This defines the precise thermal limits required to maintain a balance between a crisp crust and a succulent core without a gluten network.

These results suggest a promising dual role for the OSF matrix as both a physical barrier and a bioactive carrier, though further studies are needed to fully elucidate the underlying molecular mechanisms of its bioactive role. Beyond these demonstrated findings, this study opens new avenues for food engineering, specifically in tailoring the porosity of plant based coatings through hydrocolloid synergy. Future research should prioritize investigating these thermal regulation hypotheses, evaluating the scale-up of OSF-based systems in industrial frying lines, and assessing their performance under repeated frying cycles to ensure long-term oxidative and sensory stability. Ultimately, valorizing oleaster seeds into such specialized coating systems provides a sustainable and innovative perspective to meet the increasing demand for high quality, safe, and functional gluten-free seafood products.

Author contribution Meryem Göksel Saraç: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization; Tugba Dedebas: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. Özlem Pelin Can: Conceptualization, Methodology, Formal analysis, Investigation, Resources.

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Data availability Data will be made available on request.

Declarations

Competing interest The authors declare no conflict of interest.

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