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Effects of Nettle Seed Oil-Enriched Gelatin Coating on the Microbial, Chemical, and Sensory Qualities of Trout Burgers

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Abstract: This study evaluated the effects of gelatin-based edible coatings enriched with nettle seed oil on the microbial, chemical, and sensory properties of trout burgers during refrigerated storage (4 ± 1°C) for 16 days. Four experimental groups were prepared: control (C), gelatin coating (GC), gelatin coating with 1% nettle seed oil (GC1), and gelatin coating with 2% nettle seed oil (GC2). Samples were analyzed on days 0, 4, 8, 12, and 16 for microbiological counts, TBARS, TVB-N, pH, and sensory attributes using standard microbiological and chemical methods. The results showed that coating application slowed the increase in microbial counts and chemical spoilage indicators compared to the control group. In particular, oil-enriched coatings (GC1 and GC2) were generally associated with lower TBARS and TVB-N values during storage. Sensory scores declined in all groups over time; however, coated samples maintained acceptable levels for a longer period compared to the control. Overall, gelatin-based coatings enriched with nettle seed oil contributed to delaying quality deterioration in trout burgers during refrigerated storage, highlighting a novel and sustainable preservation approach.

Keywords: Fish burger, gelatin coating, nettle seed oil, microbial quality, lipid oxidation, sensory properties.

Isırgan Tohumu Yağı ile Zenginleştirilmiş Jelatin Kaplamanın Alabalık Burgerlerinin Mikrobiyal, Kimyasal ve Duyusal Özellikleri Üzerindeki Etkileri

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Öz: Bu çalışma, ısırgan otu tohumu yağı ile zenginleştirilmiş jelatin bazlı yenilebilir kaplamaların, 16 gün boyunca soğutulmuş depolama (4 ± 1 °C) sırasında alabalık burgerlerinin mikrobiyal, kimyasal ve duyusal özellikleri üzerindeki etkilerini değerlendirmiştir. Dört deney grubu hazırlanmıştır: kontrol (C), jelatin kaplama (GC), %1 ısırgan otu tohumu yağı içeren jelatin kaplama (GC1) ve %2 ısırgan otu tohumu yağı içeren jelatin kaplama (GC2). Örnekler, standart mikrobiyolojik ve kimyasal yöntemler kullanılarak 0, 4, 8, 12 ve 16. günlerde mikrobiyolojik sayımlar, TBARS, TVB-N, pH ve duyusal özellikler açısından analiz edilmiştir. Sonuçlar, kaplama uygulamasının, kontrol grubuna kıyasla mikrobiyal sayımlardaki ve kimyasal bozulma göstergelerindeki artışı yavaşlattığını göstermiştir. Özellikle, yağ ile zenginleştirilmiş kaplamalar (GC1 ve GC2), depolama sırasında genellikle daha düşük TBARS ve TVB-N değerleriyle ilişkilendirilmiştir. Duyusal puanlar zamanla tüm gruplarda azalmıştır; ancak, kaplanmış numuneler kontrol grubuna kıyasla daha uzun süre kabul edilebilir seviyelerde kalmıştır. Genel olarak, ısırgan otu tohumu yağı ile zenginleştirilmiş jelatin bazlı kaplamalar, soğutulmuş depolama sırasında alabalık burgerlerinde kalite bozulmasını geciktirmeye katkıda bulunarak yeni ve sürdürülebilir bir koruma yaklaşımını ortaya koymaktadır.

Anahtar Kelimeler: Balık burger, jelatin kaplama, ısırgan tohumu yağı, mikrobiyal kalite, lipid oksidasyonu, duyusal özellikler.

INTRODUCTION

Fish and fish products are highly valued for their nutritional quality, particularly due to their high protein content, essential amino acids, and polyunsaturated fatty acids (Pandey & Upadhyay, 2022; Tsoupras et al., 2022; Abera & Adimas, 2024; Noreen et al., 2025). These components contribute positively to human health, yet they also make fish products highly perishable because of their susceptibility to microbial growth and lipid oxidation (Mei et al., 2019; Ali et al., 2022). Such deterioration processes lead to quality loss, reduced shelf life, and decreased consumer acceptability, highlighting the need for effective preservation strategies in seafood products.

In recent years, the growing demand for convenient and ready-to-eat seafood products has increased the popularity of fish burgers, particularly among younger consumers who are shifting toward fast food options

(Branciari et al., 2017). The production and consumption of fish burgers have risen in parallel with the increasing demand for processed fish products. Factors such as the expansion of the working population, urbanization, and fast-paced lifestyles have driven consumers toward foods that can be prepared quickly and consumed easily. This trend has expanded the market share of ready-to-eat and functional products such as fish burgers. Moreover, the younger generation's interest in fast-food-style products positions fish burgers as a healthier alternative to traditional meat-based fast food. Thus, fish burgers are increasingly regarded as an option that aligns both with the pursuit of healthy eating and the demands of modern lifestyles (Shahin et al., 2016; Uğur, 2018; Duman, 2020).

However, the growing popularity of fish burgers also presents new challenges in terms of shelf life and quality control. Lipid oxidation, microbial spoilage, and changes in sensory characteristics remain major factors limiting consumer acceptance. Therefore, the development of natural and sustainable preservation methods has become a critical requirement for fish burgers, both from an industrial production perspective and in meeting consumer expectations (Lacumin et al., 2022).

Edible coatings have emerged as a promising approach to extend the shelf life of perishable foods by forming a protective barrier that reduces oxygen transfer, moisture loss, and microbial contamination (Eser & Doğruer, 2022; Mathura et al., 2025). Gelatin-based coatings, in particular, are widely used due to their film-forming ability, biodegradability, and transparency, and they can serve as carriers for bioactive compounds with antioxidant and antimicrobial properties. Essential oils have been extensively studied in this context; however, their high volatility, strong aroma, and potential sensory limitations may restrict their practical application in fish products (Rather et al., 2022; Arana-Linares et al., 2025; Kumar et al., 2025).

Plant-derived additives, particularly essential oils, have been extensively studied for their antioxidant and antimicrobial properties in edible coating systems (Alemu et al., 2025; Singh et al., 2022). However, essential oils are characterized by high volatility, strong aroma, and potential sensory limitations, which may restrict their practical application in food systems. In contrast, fixed oils, such as nettle seed oil, have received relatively limited attention in this context.

Nettle (*Urtica dioica* L.) seed oil has recently attracted scientific interest due to its rich composition of bioactive compounds. Studies have shown that it contains high levels of unsaturated fatty acids, mainly linoleic and linolenic acids, as well as sterols (β-sitosterol as the predominant component) and tocopherols (γ-tocopherol as the major fraction), which are associated with antioxidant activity and health-promoting properties (Đurović et al., 2024; Mitrović et al., 2025). These compounds contribute to oxidative stability and provide anti-atherogenic, anti-thrombogenic, and hypocholesterolemic potential, highlighting the nutritional and functional relevance of nettle seed oil (Jafari et al., 2020; Petkova et al., 2020). Although nettle has long been recognized as a medicinal and nutritional plant, its seed oil remains underexplored in food preservation applications

Despite this promising composition, no published studies have investigated its incorporation into gelatin-based edible coatings for fish products. Therefore, this study aimed to evaluate the effects of gelatin-based coatings enriched with different concentrations of nettle seed oil on microbial growth, lipid oxidation (TBARS), protein degradation (TVB-N), pH changes, and sensory quality of trout burgers during refrigerated storage. It was hypothesized that nettle seed oil would contribute to delaying lipid oxidation and microbial growth while maintaining acceptable sensory properties, thereby providing a novel and sustainable preservation strategy for fish products.

MATERIAL AND METHOD

Material: Rainbow trout (*Oncorhynchus mykiss)* fillets were obtained from the Faculty of Fisheries, Atatürk University (Erzurum, Türkiye). Nettle seed oil (cold-pressed, non-volatile) was purchased from a local herbal supplier (Erzurum, Türkiye). Gelatin and Tween 80 (emulsifier) were supplied by Sigma-Aldrich (USA).

Method

***Preparation of Gelatin-Based Coatings with Nettle Seed Oil*:** Gelatin-based coatings were prepared following the method of Andevari & Rezaei (2011). Gelatin powder (4 g) was dissolved in 100 mL of distilled water under continuous stirring for 15 minutes. Glycerol was added at 0.30 g per g of gelatin as a plasticizer, and the solution was maintained at 55°C for 30 minutes. Nettle seed oil was incorporated at concentrations of 1% and 2% (v/v), emulsified with Tween 80 (0.25% v/v) to ensure homogeneous dispersion

***Preparation of Rainbow Trout Burgers*:** Fish burgers were prepared according to the procedure described by Shabani et al. (2021). Fish fillets were minced using a meat grinder. The formulation included 2% salt, 2% mixed spices (curry powder, black pepper, and turmeric), 5% bread crumbs, 0.5% sugar, 1.5% garlic powder, and 4% onion powder. All ingredients were thoroughly blended to obtain a uniform paste. The prepared fish mixture was then shaped into circular burgers, each approximately 1 cm thick, 10 cm in diameter, and weighing 100 ± 5 g.

Coating Application and Storage: Fish burger samples were immersed in the designated coating solutions for 2 minutes, drained, and air-dried at ambient temperature for 10 minutes to allow film formation. Samples were packaged in sterile polyethylene containers and stored under refrigeration (4 ±1 °C) for 16 days. Analyses were performed at regular intervals throughout the storage period (days 0, 4, 8, 12, and 16). All experimental measurements were carried out in two independent replicates to ensure reproducibility. Fish burgers were randomly divided into four groups:

C (Control): Uncoated

GC: Gelatin coating

GC1: Gelatin coating + 1% nettle seed oil

GC2: Gelatin coating + 2% nettle seed oil

Chemical analysis: The pH of fish burgers was determined by homogenizing 5 g of sample with 50 mL of distilled water using an Ultra-Turrax homogenizer, and the values were measured with a calibrated pH meter (Bakır et al., 2025).

TVB-N content was determined using the microdiffusion procedure described by Malle & Tao (1987), with slight modifications. 40 g of homogenized sample was extracted with 80 mL of 7.5% trichloroacetic acid (TCA), centrifuged, and filtered through Whatman No. 3 paper. The filtrate was alkalized with 5 mL NaOH solution, distilled, and titrated against 0.1 N H_2SO_4 until a stable pink endpoint was reached. Values were calculated according to the formula:

TVB-N (mg/100 g)= n×16.8 where n is the volume (mL) of 0.1 N H_2SO_4 consumed during titration. Results were expressed as mg per 100 g of sample.

Lipid oxidation was assessed following the procedure of Lemon (1975). Approximately 2 g of sample was homogenized with 12 mL of TCA solution and filtered through Whatman No. 1 paper. Three milliliters of the filtrate were combined with 3 mL of 0.02 M thiobarbituric acid (TBA) solution, cooled, and centrifuged. The absorbance of the reaction mixture was recorded at 532 nm using a UV–Vis spectrophotometer. TBARS values were expressed as µmol malondialdehyde (MDA) equivalents per kilogram of sample.

Microbial analysis: 10 g of sample was aseptically transferred into sterile stomacher bags containing 90 mL of 0.1% buffered peptone water and homogenized. Serial dilutions were prepared and plated using the spread plate technique. The inoculated plates were incubated under conditions specific to each microorganism, as summarized in Table 1 (Harrigan, 1998).

Table 1. Incubation conditions for microbiological analyses.

Microorganisms	Agar	Incubation
Total Aerobic Mesophilic Bacteria	Plate Count Agar	37°C, 48 h
Psychrophilic Bacteria	Plate Count Agar	7°C, 10 days
Yeast and Mold	Potato Dextrose Agar (PDA)	25°C, 5 days

Sensory analysis: Sensory evaluation was conducted by eight trained panelists. The panelists assessed the trout burgers in terms of odor, color, and overall acceptability, using a five-point hedonic scale (1 = very undesirable, 5 = very desirable). A score of ≤2 was considered the rejection limit. The methodology was adapted from Elsheikh & Bağdatlı (2024), with minor modifications to fit the design of the present study. Each sample was labeled with random three-digit codes and presented in randomized order under controlled conditions to minimize bias. Prior to the evaluation, orientation sessions were organized to standardize the recognition of sensory attributes among panelists. All participants were trained, joined voluntarily, and provided verbal consent after being informed about the study objectives and potential risks. According to national regulations, formal ethics committee approval was not required for this type of sensory study; however, the research was conducted in accordance with ethical principles, ensuring voluntary participation without coercion, confidentiality of personal information, and the right to withdraw at any stage without consequence. Results were expressed as mean scores for each sensory attribute.

Statistical analysis: All analyses were conducted in duplicate to ensure reproducibility. Data were analyzed using two-way ANOVA with storage day and treatment group as fixed factors. When significant differences were detected ($p<0.05$), Duncan's multiple range test was applied as the post-hoc test. Different lowercase letters in the tables indicate significant differences among storage days within the same group, while identical letters denote no significant difference.

RESULTS

Effects of gelatin–nettle seed oil coatings on chemical and microbial quality parameters of trout burgers during storage are presented in Table 2. The progressive increase in TVB-N values observed in trout burgers during refrigerated storage reflects the advancement of microbial spoilage and the consequent decline in product quality. In the control group (C), TVB-N rose from 10.54 mg/100 g on day 0 to 25.98 mg/100 g by day 16, representing the highest level of deterioration and exceeding the generally accepted limit of 25–30 mg/100 g (Šimat et al., 2025). In contrast, gelatin coating (GC) and, more effectively, gelatin coatings enriched with nettle seed oil (GC1 and GC2) significantly retarded TVB-N accumulation ($p<0.05$). Notably, the GC2 group exhibited a value of 16.62 mg/100 g at day 16, which was markedly lower than the control, underscoring the protective effect of nettle seed oil in limiting protein degradation and extending product shelf life.

The increase in TBARS values observed in trout burgers during refrigerated storage indicates the progression of lipid oxidation, a key factor in the quality deterioration of fish products. In the present study, the control group (C) exhibited the highest TBARS level (6.95 µmol MDA/kg at day 16), while gelatin coatings enriched with nettle seed oil (GC1 and GC2) significantly inhibited TBARS formation

($p<0.05$). The GC2 group showed the lowest value (4.95 µmol MDA/kg), suggesting that nettle seed oil contributed to oxidative stability through its antioxidant properties. According to Lacumin et al. (2022), indicated that values below approximately 8 nmol/g correspond to fresh, non-rancid quality, values between 9–20 nmol/g reflect the onset of slight rancidity, and values above 21 nmol/g denote advanced rancidity and spoilage, rendering the product unacceptable. In the present study, all coated groups remained within the non-rancid range throughout storage, whereas the control group approached the upper limit, confirming the protective effect of nettle seed oil in delaying lipid oxidation. These findings align with previous reports demonstrating that edible coatings enriched with natural antioxidants can effectively suppress lipid oxidation and extend the shelf life of fish products.

The pH values of trout burgers showed a gradual decline during refrigerated storage, reflecting microbial metabolism and the accumulation of acidic compounds. In the present study, the control group decreased from 6.35 on day 0 to 5.99 on day 16, while nettle seed oil-enriched coatings (GC1 and GC2) maintained slightly lower pH values, with GC2 reaching 5.78 at day 16.

The TMAB values of trout burgers increased steadily during refrigerated storage, indicating microbial proliferation and progressive spoilage. In the present study, the control group (C) reached 7.33 log CFU/g by day 16, surpassing the microbiological limit of 7 log CFU/g recommended by the ICMSF (1998) for fresh and marine fish products (Emir Çoban & Keleştemur, 2017). In contrast, samples coated with gelatin–nettle seed oil formulations (GC1 and GC2) exhibited significantly lower TMAB counts throughout the storage period ($p<0.05$), with GC2 maintaining the lowest microbial load (5.94 log CFU/g at day 16). These findings suggest that nettle seed oil may contribute to microbial inhibition and shelf-life extension, consistent with previous reports showing that oils incorporated into edible coatings can effectively suppress bacterial growth in fish products.

In the control group (C), the TPB level reached 6.73 log CFU/g at the end of day 16, approaching the critical threshold for spoilage. In contrast, samples treated with gelatin–nettle seed oil coatings exhibited significantly lower TPB values throughout the storage period compared to the control group ($p<0.05$). Specifically, group GC2 maintained the lowest TPB value at 5.58 log CFU/g on day 16. These findings demonstrate that the application of gelatin–nettle seed oil coatings effectively suppresses spoilage bacteria that proliferate under cold storage conditions.

During cold storage, total yeast-mold counts (TYM) in trout burgers increased in the control group on days 12 and 16. In the control group, TYM values reached 3.12 log CFU/g by day 16, whereas this increase was significantly limited in the coated groups. Notably, the GC2 group remained stable at 2.00 log CFU/g throughout the entire storage period and most effectively suppressed yeast and mold growth.

Table 2. Chemical and microbiological changes in fish burgers with gelatin–nettle seed oil coatings during refrigerated storage.

	Storage days	**Groups**			
		C	**GC**	**GC1**	**GC2**
TVB-N	0	10.54 ± 0.09^{b}	9.78 ± 0.50^{ab}	9.40 ± 0.54^{a}	9.18 ± 0.25^{a}
	4	13.75 ± 0.41^{c}	11.74 ± 0.47^{b}	10.50 ± 0.62^{a}	9.94 ± 0.08^{a}
	8	18.51 ± 0.46^{d}	14.82 ± 0.36^{c}	12.50 ± 0.62^{b}	10.64 ± 0.76^{a}
	12	20.77 ± 0.38^{d}	17.83 ± 0.53^{c}	14.96 ± 0.84^{b}	13.01 ± 0.03^{a}
	16	25.98 ± 0.23^{d}	22.44 ± 0.62^{c}	18.73 ± 0.53^{b}	16.62 ± 0.65^{a}
TBARS	0	3.13 ± 0.21^{b}	2.88 ± 0.16^{ab}	2.92 ± 0.05^{ab}	2.32 ± 0.36^{b}
	4	3.99 ± 0.31^{a}	3.58 ± 0.51^{ab}	3.01 ± 0.20^{ab}	2.79 ± 0.46^{b}
	8	3.81 ± 0.67^{a}	4.16 ± 0.22^{a}	3.72 ± 0.39^{a}	3.39 ± 0.22^{a}
	12	5.99 ± 0.47^{b}	5.06 ± 0.11^{ab}	4.63 ± 0.43^{b}	4.18 ± 0.19^{a}
	16	6.95 ± 0.40^{b}	6.26 ± 0.24^{b}	5.16 ± 0.14^{a}	4.95 ± 0.09^{a}
pH	0	6.35 ± 0.19^{a}	6.16 ± 0.11^{a}	6.29 ± 0.05^{a}	6.08 ± 0.09^{a}
	4	6.15 ± 0.14^{a}	6.23 ± 0.12^{a}	6.26 ± 0.12^{a}	6.12 ± 0.03^{a}
	8	6.07 ± 0.07^{a}	6.13 ± 0.07^{a}	6.13 ± 0.10^{a}	6.05 ± 0.07^{a}
	12	5.98 ± 0.09^{a}	6.04 ± 0.05^{a}	6.00 ± 0.00^{a}	5.93 ± 0.03^{a}
	16	5.99 ± 0.02^{a}	6.07 ± 0.14^{a}	5.88 ± 0.17^{a}	5.78 ± 0.10^{a}
TMAB	0	3.32 ± 0.14^{b}	3.08 ± 0.10^{ab}	3.07 ± 0.07^{ab}	2.80 ± 0.08^{a}
	4	4.90 ± 0.30^{a}	3.80 ± 0.19^{ab}	4.02 ± 0.17^{b}	3.20 ± 0.17^{c}
	8	5.79 ± 0.31^{a}	4.24 ± 0.16^{b}	4.89 ± 0.16^{b}	4.50 ± 0.38^{b}
	12	6.58 ± 0.19^{b}	4.99 ± 0.13^{a}	5.31 ± 0.14^{a}	5.08 ± 0.12^{a}
	16	7.33 ± 0.28^{c}	6.53 ± 0.16^{b}	6.21 ± 0.22^{ab}	5.94 ± 0.08^{b}
TPB	0	2.18 ± 0.14^{a}	2.23 ± 0.16^{a}	2.24 ± 0.21^{a}	2.14 ± 0.18^{a}
	4	4.22 ± 0.36^{a}	3.50 ± 0.63^{a}	3.40 ± 0.43^{a}	3.03 ± 0.06^{a}
	8	5.41 ± 0.46^{a}	4.27 ± 0.08^{b}	4.32 ± 0.24^{b}	3.99 ± 0.02^{b}
	12	6.02 ± 0.04^{c}	5.06 ± 0.12^{b}	4.93 ± 0.09^{b}	4.51 ± 0.24^{a}
	16	6.73 ± 0.37^{b}	6.11 ± 0.19^{ab}	5.58 ± 0.60^{a}	5.13 ± 0.17^{a}
TYM	0	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}
	4	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}
	8	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}
	12	2.94 ± 0.91^{b}	2.13 ± 0.18^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}
	16	3.12 ± 0.08^{b}	2.40 ± 0.25^{a}	2.08 ± 0.10^{a}	2.00 ± 0.00^{a}

Values are expressed as mean ± standard deviation (n = 2). Different lowercase letters in the same row (same storage day) indicate significant differences among treatment groups ($p<0.05$). Different lowercase letters in the same column (within the same treatment group) indicate significant differences among storage days ($p<0.05$), according to Duncan's multiple range test.

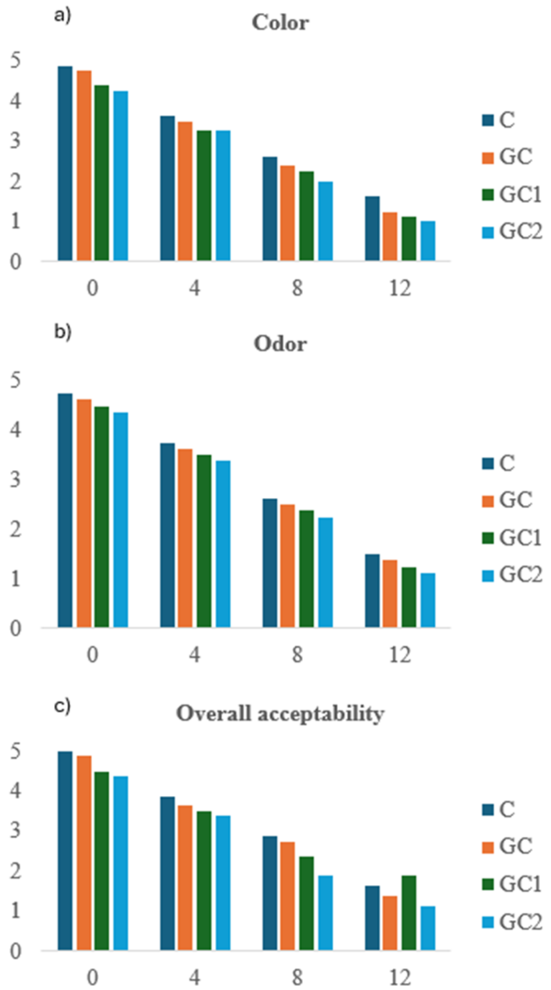

Figure 1. Sensory changes in fish burgers with gelatin–nettle seed oil coatings during refrigerated storage. C: Control (untreated); GC: Gelatin coating; GC1: Gelatin coating + 1% nettle seed oil; GC2: Gelatin coating + 2% nettle seed oil.

Sensory changes in fish burgers coated with gelatin–nettle seed oil during refrigerated storage are presented in Figure 1 (a–c). At the beginning of storage (day 0), the control group (C) generally received slightly higher sensory scores compared to coated samples, which may be attributed to panelists' familiarity with the untreated product and the initial perception of the added oil. However, this advantage diminished during storage. From day 4 onwards, a decline in sensory scores was observed in all treatments, with a more pronounced decrease in the control group. By day 12, overall acceptability scores in the control group approached or fell below the rejection threshold (score ≤2), indicating loss of consumer acceptability. Coated samples generally exhibited relatively higher sensory scores compared to the control, suggesting a partial delay in sensory deterioration. However, this effect was not consistent across all groups and attributes, and differences were moderate and sometimes not statistically significant ($p > 0.05$). GC1 tended to maintain a more balanced profile in odor and overall acceptability, whereas GC2 occasionally showed lower sensory scores due to a more pronounced oil-related aroma. Therefore, the sensory advantage of oil-enriched coatings should be interpreted cautiously. Therefore, the sensory advantage of oil-enriched coatings should be interpreted cautiously. Among the coated samples, the GC1 group generally showed a more balanced profile in terms of odor and overall acceptability during storage. However, this trend was not uniformly observed across all time points and attributes. The GC2 group, while effective in preserving chemical and microbial quality, showed slightly lower sensory scores at certain stages, possibly due to a more pronounced oil-related aroma. Overall, the results indicate that gelatin-based coatings, particularly when enriched with moderate levels of nettle seed oil, can contribute to maintaining sensory quality during storage. However, the effect is not absolute and should be considered in combination with other quality parameters.

DISCUSSION

The results clearly demonstrate that gelatin–nettle seed oil coatings effectively preserved the chemical and microbial quality of trout burgers during refrigerated storage. The retardation of TVB-N accumulation in GC1 and GC2 groups indicates that nettle seed oil slowed protein degradation and microbial spoilage. These results are consistent with previous findings on fish products. Mirza et al. (2023) reported that natural coatings based on green tea extract and olive leaf extract effectively reduced TVB-N levels in tilapia compared to untreated samples. In their study, untreated tilapia reached 67.92 mg/100 g after prolonged storage, while coated groups remained significantly lower (49.73–49.97 mg/100 g). These findings highlight that the incorporation of bioactive compounds into edible coatings can mitigate protein degradation and microbial spoilage, thereby extending the shelf life of fish products under different storage conditions. Similarly, Sayyari et al. (2021) demonstrated that nanocomposite edible coatings enriched with fennel oil effectively lowered TVB-N levels in rainbow trout fillets during storage. They attributed this reduction to the phenolic compounds in fennel oil, which suppressed bacterial growth and limited the oxidative deamination of non-protein nitrogen compounds. In both studies, a direct relationship between bacterial population and TVB-N production was evident.

The inhibition of TBARS formation by GC1 and GC2 highlights the antioxidant properties of nettle seed oil. Comparable results were reported by Sáez et al. (2020), who demonstrated that tannin-enriched alginate–chitosan coatings delayed lipid oxidation in trout fillets, and by Hashemi et al. (2023), who showed that alginate coatings with nanoencapsulated *Carum copticum* oil reduced lipid oxidation in trout burgers. In their study, the encapsulated oil consistently maintained lower TBA values throughout storage compared to the control, an effect attributed to the gradual release of bioactive compounds and the enhanced oxidative stability provided by the coating matrix. These results confirm that edible coatings enriched with natural antioxidants whether nettle seed oil or oils such as *Carum copticum* can effectively retard lipid oxidation.

The stabilization of pH values in GC1 and GC2 groups suggests an inhibitory effect of nettle seed oil on microbial metabolism. Comparable findings were reported by Uçak & Fadıloğlu (2020), who investigated anchovy burgers supplemented with garlic peel extract (GPE). They observed that GPE-treated samples maintained lower pH values than the control ($p<0.05$), which was attributed to the antimicrobial constituents of GPE.

Microbial counts (TMAB, TPB, TYM) were significantly lower in GC1 and GC2 groups compared to the control, confirming the antimicrobial and antifungal activity of nettle seed oil. Similar observations were reported by Albertos et al. (2019), who investigated the effects of bio-based seaweed edible films on the microbial stability of fish burgers. Their study showed that films containing seaweed extracts (FHE, FPE) were more effective than plain seaweed films (FH, FP) in limiting total aerobic mesophilic growth, particularly during the early stages of storage. Comparable findings were also presented by GhareAghaji et al. (2021), who studied rainbow trout fillets coated with salep containing orange peel oil. They observed that the initial microbial load of fish samples was approximately 4.48 log CFU/g, indicating freshness, and emphasized that the maximum acceptable initial microbial count for freshwater fish such as rainbow trout is about 6 log CFU/g. Their study further highlighted that initial contamination, packaging, and storage temperature are critical determinants of shelf life. The application of orange peel essential oil-based coatings effectively reduced microbial growth, thereby extending product stability. Taken together, these findings support the conclusion that edible coatings enriched with natural antimicrobial agents such as nettle seed oil, seaweed extracts, or citrus peel essential oil can effectively suppress mesophilic aerobic bacteria and extend the microbial shelf life of fish-based products under cold storage conditions.

Gelatin–nettle seed oil coatings also showed inhibitory activity against psychrotrophic bacteria, significantly reducing their proliferation under cold storage conditions. Similar results have been reported in the literature. Uçak (2020) observed that fish burger groups prepared with the addition of pomegranate seed extract exhibited significantly lower total psychrotrophic bacteria counts compared to the control group. The observed reduction in microbial growth may be attributed to the suggested antimicrobial effect of nettle seed oil, which is rich in phenolic compounds and unsaturated fatty acids. Furthermore, Mehrabi et al. (2024) reported that chitosan coatings enriched with ginger essential oil significantly inhibited the growth of psychrotrophic bacteria in salmon.

Gelatin–nettle seed oil coatings exhibited clear antifungal activity, effectively suppressing yeast and mold growth during refrigerated storage of trout burgers. Similarly, Aref et al. (2022) reported that edible coatings containing chitosan, nanochitosan, and clove oil extended the shelf life of mullet steaks, with the nanochitosan coating, in particular, yielding the lowest yeast–mold counts. Anwar et al. (2022) demonstrated that xanthan gum coatings enriched with black tea extract effectively extended the shelf life of zander fillets by limiting yeast and mold proliferation and maintaining product quality. These outcomes further support the antifungal potential of natural plant-derived compounds incorporated into edible coatings, underscoring their role in improving microbial stability and prolonging the shelf life of fish-based products.

The sensory results suggest that functional coatings enriched with nettle seed oil were generally more effective than untreated or plain gelatin-coated samples in maintaining sensory attributes during storage. Although untreated burgers initially exhibited the best sensory quality, they deteriorated rapidly, highlighting the importance of protective coatings. GC1 appeared to provide a more balanced profile, indicating that moderate enrichment (1%) may offer the optimal compromise between flavor acceptability and preservation efficacy. These findings are in line with previous reports highlighting the antioxidative and antimicrobial properties of natural oils in food preservation. Elsheikh & Bağdatlı (2024) reported that chitosan coatings enriched with orange essential oil effectively extended the shelf life of fish burgers by preserving sensory quality; while the control group was rejected on day 9, coated samples remained acceptable until day 18. Similarly, Mezhoudi et al. (2022) found that Mustelus mustelus fillets coated with gelatin enriched with Moringa oleifera extract consistently achieved the highest sensory scores for odor, color, and overall acceptability during refrigerated storage. Taken together, these studies support the present findings, demonstrating that gelatin–nettle seed oil coatings, particularly at 1% concentration, represent a promising strategy to extend shelf life and consumer acceptability of fish burgers by preserving sensory quality throughout refrigerated storage.

CONCLUSION

In conclusion, gelatin-based edible coatings enriched with nettle seed oil contributed to delaying quality deterioration in trout burgers during refrigerated storage.

The GC2 formulation (2% nettle seed oil) was the most effective in preserving chemical and microbiological quality, significantly reducing lipid oxidation, protein degradation, and microbial growth compared to the control. However, sensory evaluation indicated that GC1 (1% nettle seed oil) provided a more balanced profile, maintaining odor, color, and overall acceptability at relatively higher levels during storage. These findings highlight that while GC2 offers stronger preservation efficacy in terms of chemical and microbial stability, GC1 achieves a better compromise between sensory acceptability and product integrity. Therefore, nettle seed oil-enriched gelatin coatings represent a promising and sustainable preservation strategy, with GC1 appearing optimal for balancing consumer perception and shelf-life extension.

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