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GELATIN PRODUCTION FROM RAINBOW TROUT (*Oncorhynchus mykiss*) SKINS AND EVALUATION OF ITS TECHNOLOGICAL PROPERTIES

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Abstract: Gelatin production from fish-processing by-products has gained attention as a sustainable strategy for value-added utilization of aquatic resources. In this study, gelatin was extracted from rainbow trout (*Oncorhynchus mykiss*) skins and its physicochemical, structural, and functional properties were evaluated in comparison with commercial bovine gelatin. Compared with bovine gelatin (220±3.00 g), trout gelatin displayed a milder gel network characterized by a gel strength of 95.1±5.00 g, a pH of 4.78±0.23, and a water-holding capacity of 13.92±0.73 mL water/g protein, reflecting distinct structural and functional behavior rather than reduced quality. In contrast, the high protein content (95.30±0.41%) indicated considerable compositional purity. Functional analyses revealed distinct interfacial advantages for trout gelatin. Oil-binding capacity was significantly higher (1.17±0.10 mL oil/g protein) than that of bovine gelatin ($P<0.05$). Although emulsifying activity index and initial foaming capacity were similar or lower, trout gelatin demonstrated markedly greater emulsion stability and long-term foam stability ($P<0.05$). Zeta potential values were low for both gelatins, suggesting that stabilization mechanisms were governed more by steric interactions and viscoelastic interfacial film formation than by electrostatic repulsion. FTIR spectra showed characteristic amide bands (amide I, II, III, A, and fingerprint regions) in both samples, confirming successful conversion of collagen to gelatin and indicating comparable chemical structures. Therefore, the observed functional differences are likely associated with molecular organization and amino acid composition rather than major structural variations. Overall, rainbow trout skin gelatin can be considered a promising alternative to bovine gelatin, particularly in food systems where emulsion and foam stability or lipid interaction are more critical than high gel strength. Its production from processing by-products also supports sustainable waste valorization in the food industry.

Keywords: Rainbow trout gelatin, Fish by-products, Technological properties, Gel strength, Emulsion, Foaming

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1. Introduction

Growing pressure on natural resources, the progressive loss of biodiversity, and the visible impacts of climate change highlight the need for food systems that are more sustainable, resilient, and resource efficient. In this context, strategies aimed at reducing food losses, improving waste valorization, and promoting the recycling and re-use of by-products have become global priorities. Policy initiatives such as the European Green Deal and national Green Deal Action Plans emphasize circular economy approaches and encourage research on the recovery and utilization of agricultural and food processing by-products (Anonym, 2021).

Fish processing is one of the sectors where inadequate waste utilization results in both economic losses and environmental problems. Global fish production reached approximately 185 million tons in 2022 and is projected to increase to about 205 million tons by 2032; however, only a portion of this production is suitable for direct human consumption (FAO, 2024). Depending on species and processing methods, 20–80% of the fish may be converted into by-products, a substantial portion of which is often discarded, contributing to environmental pollution (Yathisha et al., 2019).

Fish by-products, including skins, heads, bones, and scales, are rich sources of valuable biomolecules such as proteins, vitamins, minerals, omega-3 fatty acids, enzymes, antioxidants, and bioactive peptides (Abuine et al., 2019; Yathisha et al., 2019; Idowu et al., 2020). Since protein constitutes the second most abundant component of fish tissues, these by-products typically contain 8–35% protein on a dry basis (Sila and Bougatef, 2016). A considerable proportion of this protein is collagen, particularly in skins and connective tissues, where levels may approach 30%, highlighting their potential as raw materials for gelatin production.

Gelatin, a partially hydrolyzed derivative of collagen, is traditionally produced from porcine and bovine skins

and bones, although poultry and fish sources have also been explored. Due to its gelling, thickening, emulsifying, and stabilizing properties, gelatin is widely applied in food systems such as confectionery, dairy, bakery, and meat products, as well as in pharmaceutical and biomedical applications (Johnston-Banks, 1990; Schrieber and Gareis, 2007). Industrial gelatin production involves acid or alkaline pretreatment of collagen-rich materials followed by hot-water extraction, which disrupts the native triple-helix structure and yields soluble polypeptide chains (Tekle, 2016).

Despite the increasing global demand for gelatin, production is still dominated by porcine and bovine sources, while fish gelatin accounts for only a limited share (Alipal et al., 2021). Growing concerns regarding sustainability, environmental impact, cultural and religious restrictions, and food safety have intensified interest in alternative gelatin sources. However, fish gelatins are often characterized by lower gel strength compared to mammalian gelatins, which may limit their application in certain products. On the other hand, fish gelatin has been reported to exhibit advantageous interfacial and functional properties, such as improved emulsifying and foaming behavior, depending on species and processing conditions. However, comprehensive studies that simultaneously evaluate the interfacial, functional, and structural properties of rainbow trout skin gelatin in direct comparison with commercial bovine gelatin remain limited (Karim and Bhat, 2009).

In Türkiye, rainbow trout (*Oncorhynchus mykiss*) is widely cultivated in freshwater aquaculture systems, leading to the accumulation of significant amounts of processing residues, particularly fish skins. Official statistics show that total trout production reached 231,591 tons in 2024, highlighting the growing volume of potentially valuable by-products generated annually (TUIK, 2025). In this context, the valorization of rainbow trout skin represents an opportunity to convert low-value waste into high-value functional ingredients. Therefore, the present study aimed to extract gelatin from rainbow trout skins and to comprehensively evaluate its physicochemical, functional, interfacial, and structural properties, including gel strength, water- and oil-binding capacity, emulsifying and foaming behavior, zeta potential, and FTIR characteristics, in comparison with commercial bovine gelatin.

2. Materials and Methods

2.1. Preparation of Fish Skins

Skins of rainbow trout (*Oncorhynchus mykiss*) were obtained from fish-processing companies located in Kirsehir, Türkiye. The skins were collected immediately after filleting and transported to the laboratory under refrigerated conditions without breaking the cold chain. Upon arrival, the by-products were rinsed thoroughly with cold tap water to remove adhering flesh and surface impurities, and the excess water was drained. The cleaned skins were then cut into small pieces (approximately 0.5 × 0.5 cm) using scissors. Until further processing, the prepared samples were stored at 4 °C and kept under refrigeration to prevent quality deterioration prior to gelatin extraction.

2.2 Production of Rainbow Trout Gelatin

Gelatin was produced from fish skins following the procedure described by Boran and Regenstein (2009), with minor modifications. Briefly, the prepared skins were transferred into 500-mL Erlenmeyer flasks and subjected first to alkaline pretreatment using NaOH (0.55 N) at a solid-to-solution ratio of 1:5 (v/w) for 67.5 min. This step was followed by an acid treatment with HCl (0.1 N) at the same ratio (1:5, v/w) for 45 min. After each alkaline and acid treatment, the skins were rinsed with distilled water (1:5, v/w) at room temperature, passed through four layers of cheesecloth, and gently pressed by hand to remove excess liquid. Gelatin extraction was then carried out in a water bath (Memmert WNB45, Schwabach, Germany) using distilled water at a ratio of 1:4 (v/w), at 50 °C for 3 h. Prior to timing, the samples were equilibrated for 15 min to ensure uniform temperature between the water bath and the samples. Following extraction, the hot solution was filtered through cheesecloth to separate the residues. The resulting gelatin solutions were poured into glass trays and dried in an oven (Binder GmbH ED240, Germany) at 60 °C for approximately 72 h. The dried gelatin was obtained in sheet form and stored in polyethylene bags under dry conditions until further analysis.

Gelatin yield was calculated according to the following equation 1:

$$\text{Gelatin yield (\%)} = (\text{weight of dried gelatin} / \text{weight of fish skin}) \times 100 \quad (1)$$

2.3 Determination of Gel Strength (Bloom Value)

Gel strength was determined according to the standard Bloom method with slight modifications. A gelatin solution was prepared at a concentration of 6.67% (w/v), allowed to swell and hydrate for 1 h at 10 °C, and then completely dissolved in a water bath at 45 °C for 30 min. The resulting solutions were transferred into Bloom jars and matured at 10 °C for 16–18 h without disturbance. Gel strength was measured using a texture analyzer equipped with a 5-kg load cell and a cylindrical probe with a diameter of 1.27 cm. The maximum force required to depress the gel surface to a fixed depth was recorded and expressed as Bloom value in grams (Tekle, 2016).

2.4. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

Ten percent (w/v) gelatin solutions were prepared using distilled water. To ensure complete homogenization, the solutions were kept in a water bath at 45 °C for 30 min (Memmert WNB45, Schwabach, Germany). ATR-FTIR spectra were recorded at a resolution of 4 cm^{-1} with 16 scans per spectrum using a Bruker Tensor 27 FTIR spectrometer (Ettlingen, Germany). Spectra were collected within the mid-infrared region from 4000 to

600 cm^{-1}. All measurements were performed under the same conditions, and the average of three spectra was used for each sample. Prior to each measurement, the crystal surface was cleaned with distilled water and absolute ethanol (Cebi et al., 2016).

2.5. Zeta Potential of Gelatins

Solutions of fish gelatin (10%, w/v) were prepared using distilled water. To ensure complete dissolution, the samples were kept in a water bath at 45 °C for 30 min (Memmert WNB45, Schwabach, Germany). Subsequently, 25 µL of each sample was mixed with 2 mL of Phosphate-buffered saline (PBS) (0.01 M, pH 7.4) and analyzed using a Zetasizer Nano ZSP (Malvern, UK). Zeta potential values were reported as the mean of three independent measurements, each consisting of at least fifteen readings.

2.6. Determination of Protein Content

The protein content of fish and bovine gelatins was determined using the Kjeldahl method. Approximately 1 g of each sample was weighed into Kjeldahl digestion tubes, followed by the addition of 12 mL concentrated sulfuric acid (H_2SO_4) and one Kjeldahl catalyst tablet. The tubes were placed in the digestion unit and heated for about 4 h until the solution became clear. After cooling, 75 mL of distilled water was added to each tube, and the mixtures were subjected to distillation. During distillation, 75 mL of 33% NaOH solution was automatically introduced into the tubes, while the distillate was collected in an Erlenmeyer flask containing 25 mL of 4% boric acid solution. The process was continued until approximately 150 mL distillate had been obtained. The collected distillate was then titrated with 0.1 N HCl.

Total nitrogen was calculated using the equation 2 below, and the nitrogen value was converted to total protein using a conversion factor of 5.4 (Yıldız, 2017):

$$\text{Total nitrogen (\%)} = [(A-B) \times N \times 0.014 / \text{Sample weight}] \times 100 \quad (2)$$

where:

A = volume of 0.1 N HCl used for the sample (mL)

B = volume of 0.1 N HCl used for the blank (mL)

N = normality of HCl (0.1 N)

Sample weight: gelatin content (g)

2.7. pH Analysis

A 1% (w/v) gelatin solution was prepared using ground trout gelatin. The gelatin particles were allowed to dissolve completely in a shaking water bath at 60 °C for 30 min. After cooling to room temperature, the pH of the solution was measured using a digital pH meter (OHAUS a-AB33PH-F, Switzerland).

2.8. Emulsion Activity and Stability

The emulsion activity index (EAI) and emulsion stability index (ESI) were determined with minor modifications according to the procedure described by Zamorano-Apodaca et al. (2020). A 9-mL portion of a 0.1% (w/v) lyophilized gelatin solution was placed in a beaker, followed by the addition of 3 mL sunflower oil. The mixture was homogenized using an Ultra-Turrax (Daihan HG-15D, Seoul, Korea) at 18,000 × g for 1 min. Immediately after homogenization (0 min) and again at 10 min, 50 µL of the emulsion was withdrawn from the lower phase and diluted to 5 mL with 0.1% (w/v) sodium dodecyl sulfate (SDS). Absorbance was recorded at 500 nm using a UV–Vis spectrophotometer (Shimadzu UV-1800, Tokyo, Japan).

EAI and ESI values were calculated using the following equations 3 and 4:

$$\text{EAI } (m^2/g) = (2 \times 2.303 \times A_0) / (C \times \varphi) \quad (3)$$

where

A_0 = absorbance at 500 nm,

C = initial protein concentration (g/mL),

φ = volume fraction of oil in the emulsion.

$$\text{ESI (min)} = (A_0 \times \Delta t) / \Delta A \quad (4)$$

where

A_{10} = absorbance at 10 min,

Δt = 10 min,

$\Delta A = A_0 - A_{10}$.

2.9. Foam Capacity and Stability

Foam capacity and foam stability were evaluated with slight modifications based on the method of Zamorano-Apodaca et al. (2020). A 10-mL portion of a 0.5% (w/v) lyophilized gelatin solution was transferred into a beaker and homogenized at 14,000 × g for 1 min at room temperature using an Ultra-Turrax homogenizer (Daihan HG-15D, Seoul, Korea).

The total foam volume was recorded immediately after homogenization (0 min) and again at 3- and 10-min. Foam capacity was expressed as the foam expansion at 0 min, whereas foam stability represented the foam expansion measured at 10 min.

Foam expansion (%) was calculated using the following equation 5:

$$\text{Foam expansion (\%)} = [(A - B) / B] \times 100 \quad (5)$$

where:

A = volume of the sample at each time point (mL)

B = initial volume before homogenization (mL)

2.10. Oil Binding Capacity and Water Holding Capacity

Oil binding capacity of the gelatins was determined with minor modifications to the procedure described by Karoud et al. (2019). Pre-weighed centrifuge tubes were filled with 50 mg of sample and weighed again. Subsequently, 1 mL of sunflower oil was added, and the tubes were left at room temperature for 1 h. During incubation, the mixtures were vortexed (Velp ZX3 Vortex Mixer, Italy) for 5 s every 15 min. The tubes were then centrifuged at 5000 rpm for 20 min (Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany), and the upper oil layer was carefully removed. For the control, the same procedure was performed using empty tubes containing only oil. Oil binding capacity was expressed as mL of oil retained per gram of protein.

Water holding capacity was evaluated according to the method described by Cobb III and Hyder (1972). A total of 50 mg of hydrolysate was placed in a centrifuge tube and mixed with 2 mL of distilled water. After vortexing for 30 s, the tubes were kept in the dark at room temperature for 6 h. Samples were subsequently centrifuged at 5000 × g for 20 min at 4 °C. The resulting supernatant was filtered through Whatman No. 1 filter paper, and the filtrate volume was recorded. Water holding capacity was calculated by subtracting the filtrate volume from the initial water volume and dividing by the sample weight, and results were expressed as mL water/g protein.

2.11. Statistical Analysis

All analyses were performed in triplicate. The results were subjected to analysis of variance (ANOVA), and significant differences among the means were determined using Tukey's multiple comparison test in JMP 9 software (SAS Institute, NC, USA). Differences were considered statistically significant at $P<0.05$.

3. Results and Discussion

3.1. Extraction Yield

Gelatin was produced from the skins of rainbow trout (*Oncorhynchus mykiss*), and the extraction procedure yielded approximately 16% (w/w) based on the mass of washed fresh skins. Previous investigations on trout skin gelatin have reported markedly lower recovery levels, such as 2.5% (Usman et al., 2025) and 8.46% (Duman, 2025). In general, extraction efficiencies for fish skin gelatins are known to vary widely, typically falling between 6% and 19%, depending on factors such as fish species, conditioning treatments applied prior to extraction, and processing temperature. Yield values are commonly expressed as the amount of dry gelatin obtained from 100 g of prepared skin material (Karim and Bhat, 2009). Accordingly, the recovery achieved in the present work is within the upper portion of the range reported for fish-derived gelatins. This outcome suggests that rainbow trout skin represents a promising raw material for gelatin manufacture and supports its utilization within sustainable by-product valorization approaches in the fish-processing industry.

3.2. Gel Strength (Bloom Value)

Gel strength represents one of the most critical functional indicators of gelatin, as it directly affects texture formation and structural stability in food formulations. It is well established that gelatins derived from fish generally exhibit lower gel firmness compared with mammalian counterparts (Gilsenan and Ross-Murphy, 2000). Commercial gelatin products are categorized according to Bloom strength, which commonly falls within the range of 100–300 g, while values above 250 g are frequently preferred in applications demanding firm gel structures (Karim and Bhat, 2009).The Bloom values measured for rainbow trout skin gelatin and commercial bovine gelatin are shown in Table 1. The gel strength of rainbow trout skin gelatin was determined as 95.1±5.00 Bloom, which was considerably lower than that of commercial bovine gelatin ($P<0.05$). Earlier studies focusing on trout skin have reported gel strengths of 104 g (Usman et al., 2025) and 100 g (Duman, 2025), indicating relatively weak gel-forming ability. The Bloom strength obtained for trout gelatin in the present work was lower than that of bovine gelatin and also below those documented for gelatins from several warm-water fish species, such as grass carp (267 g; Kasankala et al., 2007) and tilapia (224 g; da Trindade Alfaro et al., 2013). In contrast, it was comparable to values reported for cold-water species including salmon (108 g; Arnesen and Gildberg, 2007) and cod (70–90 g; Gómez-Guillén et al., 2002). Differences in gel strength among fish gelatins are primarily related to variations in amino acid composition, particularly the proportion of imino acids (proline and hydroxyproline), which contribute to the stabilization of gelatin gel networks. Extraction parameters, such as pretreatment and temperature, may further influence molecular integrity and intermolecular interactions, thereby affecting final gel structure. Although the gel strength of rainbow trout gelatin is relatively low, this characteristic does not preclude its use; rather, it may be advantageous in products where a softer or more elastic gel texture is desired, including emulsified foods, low-firmness confectionery, and edible film systems.

Table 1. Technological properties of rainbow trout and bovine gelatins*

Parameter	Rainbow trout gelatin	Bovine gelatin
Gel strength (g, Bloom)	95.1±5.00[a]	220.0±3.00[b]
Protein (%)	95.30±0.41[b]	89.70±0.63[a]
pH	4.78±0.23[a]	5.98±0.32[b]
Water-holding capacity (mL water/g protein)	13.92±0.73[a]	20.83±0.41[b]
Oil-binding capacity (mL oil/g protein)	1.17±0.10[b]	0.86±0.07[a]

*Data are expressed as mean ± standard deviation of triplicate measurements. Means indicated by different lowercase letters in the same row in the table show statistically significant differences ($P<0.05$) among the gelatins.

3.3. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis of rainbow trout skin gelatin and commercial bovine gelatin revealed absorption patterns characteristic of gelatin, confirming the presence of typical protein functional groups (Figure 1). Distinct spectral regions corresponding to amide A, amide I, amide II, and amide III vibrations were evident in both samples. The amide I band, primarily associated with C=O stretching vibrations and widely employed to assess protein secondary structure, was located at 1630.20 cm^{-1} for trout gelatin and 1628.39 cm^{-1} for bovine gelatin. These closely aligned positions indicate comparable secondary structural organization and agree with values commonly reported for gelatin (Cebi et al., 2016; Nagarajan et al., 2012). The amide II band, originating mainly from N–H bending and C–N stretching vibrations, appeared at 1526.72 cm^{-1} and 1525.10 cm^{-1}, respectively, demonstrating preservation of the peptide backbone following extraction. Amide III bands, resulting from combined C–N stretching, N–H deformation, and CH_2 vibrations with contributions from glycine and proline residues, were observed at 1240.02 cm^{-1} (trout) and 1237.18 cm^{-1} (bovine), further supporting the maintenance of structural features typical of gelatin. In the fingerprint region, absorption signals between 1083–1031 cm^{-1} are generally linked to C–O stretching vibrations of carbohydrate-related components associated with collagen proteoglycans (Kohler et al., 2007). Peaks in this region were detected at 1077.54 cm^{-1} and 1079.50 cm^{-1}, in agreement with previous findings for cold-water fish gelatins (Cebi et al., 2016). The amide A band, mainly related to O–H stretching with minor N–H contributions, was observed at 3276.54 cm^{-1} and 3278.69 cm^{-1} for trout and bovine gelatin, respectively (Hashim et al., 2010).

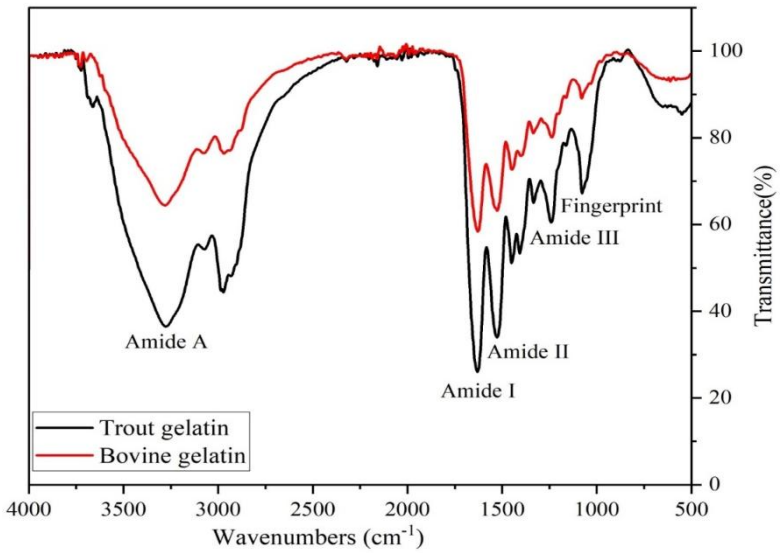

Figure 1. Fourier Transform Infrared (FTIR) spectra of gelatin extracted from rainbow trout skin and commercial bovine gelatin.

Collectively, the close correspondence of FTIR band positions indicates that the conversion of collagen to gelatin occurred without significant chemical alteration of fundamental functional groups. The similarity of the FTIR band patterns, despite differences in gel strength, indicates that variations in functional behavior are more likely associated with molecular organization and amino acid composition rather than major alterations in chemical structure. The spectra reflect structural characteristics typical of partially denatured collagen, confirming successful gelatin formation. Therefore, observed differences in technological performance between the two gelatins are unlikely to stem from major chemical structural disparities but rather from variations in molecular organization and amino acid composition.

3.4. Zeta Potential Values of Gelatins

Zeta potential is commonly used to characterize the surface charge properties of protein and peptide systems and provides insight into the electrostatic stability of colloidal dispersions. In this study, the measured zeta potential values were −3.58±0.03 mV for rainbow trout gelatin and −8.23±0.05 mV for commercial bovine gelatin ($P<0.05$). Literature indicates that higher absolute zeta potential values, irrespective of sign, promote electrostatic repulsion between particles, thereby decreasing aggregation tendencies and improving dispersion stability (Arias-Moscoso et al., 2015; Zamorano-Apodaca et al., 2020). Both gelatin samples exhibited relatively low absolute zeta potential magnitudes, suggesting that electrostatic repulsive forces alone may not be sufficient to ensure strong colloidal stabilization. Nevertheless, rainbow trout gelatin displayed better emulsion and foam stability in the present study. This observation implies that non-electrostatic mechanisms, such as steric hindrance and the development of viscoelastic interfacial protein films, may play a more prominent role in stabilizing dispersed systems than charge-based interactions. These results

indicate that, despite its limited electrostatic contribution, rainbow trout gelatin possesses functional characteristics that support its applicability in colloidal food formulations where interfacial film-forming capacity is a key determinant of stability.

3.5. Protein Analysis

The protein contents of rainbow trout gelatin and commercial bovine gelatin are summarized in Table 1. The results confirm that fish skin constitutes a protein-rich raw material and that the extraction and purification procedures yielded gelatins with high protein purity. Comparable protein levels have been reported for trout gelatin in earlier studies, including 97.14% (Üçyol, 2016), while other investigations have documented values of 71% (Usman et al., 2025) and 84.68% (Duman, 2025), demonstrating variability depending on processing conditions. Although rainbow trout gelatin exhibited a relatively high protein content, its gel strength was lower than that of bovine gelatin. This finding indicates that gel-forming capacity is not determined solely by overall protein concentration but is more closely associated with molecular characteristics, particularly amino acid composition, imino acid (proline and hydroxyproline) levels, and the stability of triple-helix-derived junction zones within the gelatin network. The high protein purity observed in trout gelatin may nevertheless be advantageous for applications where compositional quality and functional cleanliness are more critical than gel rigidity. Such properties may favor its use in edible films, coatings, and nutraceutical systems, where film-forming ability and bio-based composition are prioritized over high Bloom strength.

3.6. pH Analysis

The pH values of gelatin derived from rainbow trout skin and commercial bovine gelatin are presented in Table 1. Variations in pH among gelatins are largely influenced by the chemical pretreatments applied during extraction as well as the intrinsic properties of the raw material (Gudmundsson and Hafsteinsson, 1997). The relatively lower pH observed for trout gelatin in this study is consistent with acid-based processing conditions and may reflect residual effects of the pretreatment stage. Solution pH plays a significant role in determining gelatin functionality, as it affects the net charge of protein molecules and modulates intermolecular interactions during gel network formation. The slightly acidic character of rainbow trout gelatin may therefore contribute to reduced intermolecular association, which aligns with the comparatively lower gel strength measured in this work. Similar pH ranges have been reported for fish skin gelatins produced via acid extraction, including values of 5.25 (Usman et al., 2025) and 6.20 (Duman, 2025). When compared with other species, the pH of trout gelatin was higher than those reported for black tilapia (3.81), red tilapia (3.05), rohu (4.08), and common carp (4.05) skin gelatins, yet comparable to values documented for bovine (7.3), porcine (5.4), and tilapia (5.5) gelatins (Tekle, 2016). Beyond its influence on functionality, pH may also serve as an indirect indicator of the effectiveness of washing steps following chemical pretreatment, as insufficient removal of residual acids or salts can alter the final pH of gelatin solutions.

3.7. Emulsion Activity and Stability

The emulsifying performance of rainbow trout skin gelatin and commercial bovine gelatin was evaluated using the emulsifying activity index (EAI) and emulsion stability index (ESI) (Figure 2). The EAI values of trout gelatin (253.79 m^2/g) and bovine gelatin (255.26 m^2/g) were very similar ($p>0.05$), indicating comparable abilities of the two proteins to adsorb at the oil–water interface and facilitate emulsion formation. In contrast, a pronounced difference was observed in emulsion stability. Rainbow trout gelatin exhibited a substantially higher ESI value (451.80 min) than bovine gelatin (92.99 min), demonstrating superior capacity to maintain emulsion integrity over time ($P<0.05$). This enhanced stability may be associated with the greater molecular flexibility of fish-derived gelatin and the increased exposure of hydrophobic amino acid residues, which can strengthen interfacial film formation and reduce droplet coalescence. Proteins or peptide fractions possessing suitable amphiphilic balance and sufficient molecular size are known to form more cohesive and viscoelastic interfacial layers, thereby improving resistance to destabilization mechanisms (Klompong et al., 2007). Moreover, the amphiphilic character of peptides at the oil–water interface has been reported to play a more decisive role than peptide chain length in determining emulsifying performance (Rahali et al., 2000). Overall, these results suggest that rainbow trout gelatin has strong potential as a functional ingredient in emulsified food systems where prolonged stability is required, and may represent a viable alternative to bovine gelatin for such applications.

3.8. Foaming Capacity and Stability

The foaming behavior of rainbow trout skin gelatin and bovine gelatin is presented in Figure 3. Bovine gelatin showed a higher initial foaming capacity (FC) (63.02%) than trout gelatin (45.81%), indicating a greater ability to entrap air during foam formation ($P<0.05$). However, differences became more evident when foam stability (FS) was considered. After 10 min, trout gelatin maintained a higher FS value (14.24%) compared with bovine gelatin (10.77%), demonstrating improved resistance to foam collapse over time ($P<0.05$). Reported FC and FS ranges for fish gelatins vary widely (17.4–152.63% and 10.5–147.35%, respectively) (Ranasinghe et al., 2022), and the values obtained in the present study fall within these intervals. The relatively enhanced foam stability of trout gelatin may be associated with the higher flexibility of fish-derived gelatin chains, which facilitates the formation of more elastic and cohesive interfacial films surrounding air bubbles. Such films can slow liquid drainage and reduce bubble coalescence, thereby prolonging foam integrity. Foam formation is

governed by the migration, adsorption, and structural rearrangement of proteins at the air–water interface (Dong et al., 2008). Proteins capable of rapid interfacial adsorption and partial unfolding are better able to form viscoelastic films that enhance foam stability. In addition to molecular characteristics, factors such as protein concentration, film thickness, bulk and surface viscosity, and interfacial interactions (steric and electrostatic) also contribute to overall foam stability (Kchaou et al., 2020; Baharuddin et al., 2016). Overall, although rainbow trout gelatin produced less foam initially, it was more effective in preserving foam structure, highlighting its potential use in food systems where foam persistence is more critical than maximum foam volume.

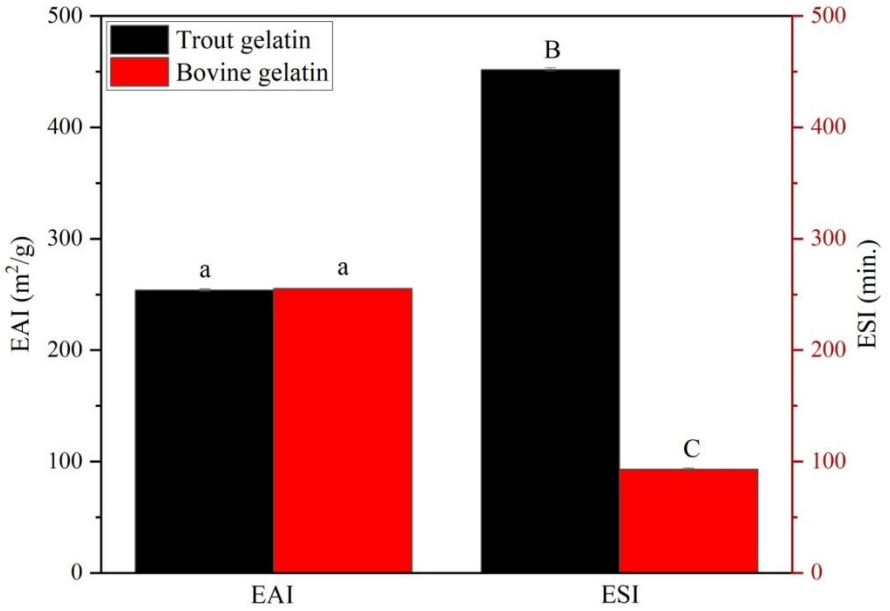

Figure 2. EAI and ESI of gelatin obtained from rainbow trout skin and commercial bovine gelatin. Error bars denote standard deviation (n = 3). Means indicated by different lowercase letters represent statistically significant differences (P<0.05) between the EAI of trout and bovine gelatins, whereas means indicated by different uppercase letters represent statistically significant differences (P<0.05) in ESI between the same samples. EAI= emulsifying activity index, ESI= emulsion stability index.

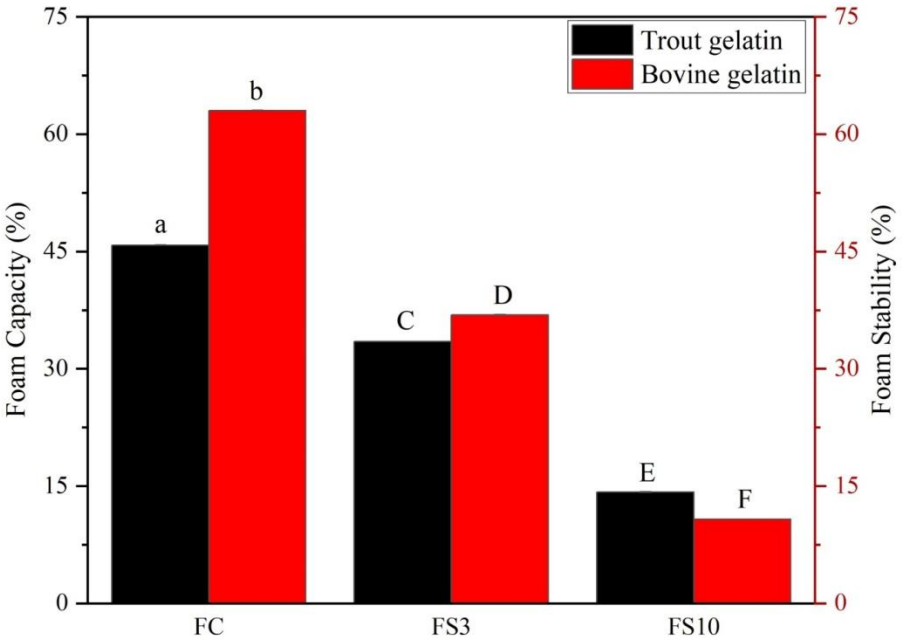

Figure 3. Foaming capacity and foam stability of gelatin obtained from rainbow trout skin and commercial bovine gelatin. Error bars denote standard deviation (n = 3). Means indicated by different lowercase letters represent statistically significant differences (P<0.05) between the foaming capacities of trout and bovine gelatins, whereas means indicated by different uppercase letters represent statistically significant differences (P<0.05) in foam stability between the same samples. FC= foam capacity, FS3= foam stability at 3 minutes, FS10= foam stability at 10 minutes.

3.9. Water-Holding and Oil-Binding Capacity

The water-holding capacity (WHC) and oil-binding capacity (OBC) of the gelatin samples are given in Table 1. Rainbow trout gelatin showed a lower WHC (13.92±0.73 mL water/g protein) than bovine gelatin (20.83±0.41 mL water/g protein), indicating a more limited ability to immobilize water within its protein network ($P<0.05$). This reduced water retention may be associated with the comparatively lower gel strength and slightly acidic pH of fish gelatin, both of which can restrict the development of a compact three-dimensional gel structure. Lower WHC values have also been related to reduced proportions of hydrophilic amino acids and lower hydroxyproline content, which influence water–protein interactions (Ninan et al., 2011).

In contrast, rainbow trout gelatin demonstrated a higher OBC (1.17±0.10 mL oil/g protein) than bovine gelatin (0.86±0.07 mL oil/g protein), suggesting a stronger affinity for lipid phases ($P<0.05$). Enhanced oil-binding behavior may result from greater exposure of hydrophobic amino acid residues and increased molecular flexibility, which facilitate interactions between protein chains and nonpolar compounds. The presence of hydrophobic residues such as tyrosine, leucine, valine, and isoleucine has been linked to improved oil absorption capacity (Ninan et al., 2011). These results indicate a functional balance in trout gelatin characterized by moderate water retention but superior lipid-binding ability. Such a profile may be advantageous in food formulations where lipid stabilization, flavor retention, and mouthfeel enhancement are desired, including comminuted meat products, bakery systems, and soup formulations. Accordingly, rainbow trout gelatin may be particularly suitable for applications where oil interaction is more critical than maximal water-holding capacity.

4. Conclusion

Gelatin was effectively extracted from rainbow trout (*Oncorhynchus mykiss*) skins, and its physicochemical, structural, and functional characteristics were evaluated in comparison with commercial bovine gelatin. The trout-derived gelatin exhibited lower gel strength and water-holding capacity, which appear to be associated with differences in molecular organization and pH conditions rather than fundamental chemical structure. Despite this, the high protein content indicated that a gelatin of considerable compositional purity was obtained. Functionally, rainbow trout gelatin demonstrated distinct advantages in interfacial applications. It showed higher oil-binding capacity, enhanced emulsion stability, and improved long-term foam stability relative to bovine gelatin. Although initial emulsifying activity and foaming capacity were similar or lower, the superior stability of emulsions and foams suggests that trout gelatin forms more resilient interfacial films. Zeta potential results further indicated that stabilization mechanisms were not predominantly electrostatic but were more likely governed by steric effects and the development of viscoelastic interfacial layers. FTIR analysis confirmed the presence of characteristic amide bands and structural features typical of gelatin, with spectra closely resembling those of bovine gelatin. This similarity demonstrates successful conversion of collagen to gelatin and indicates that the observed functional differences are mainly related to molecular flexibility and amino acid composition rather than major chemical structural changes. Overall, rainbow trout skin gelatin can be considered a promising alternative to bovine gelatin, particularly in food systems where emulsion and foam stability or lipid interaction are more critical than high gel firmness. The utilization of trout processing by-products for gelatin production also represents a sustainable approach that contributes to waste valorization and supports circular bioeconomy principles. Future studies should focus on optimizing extraction conditions, elucidating structure–function relationships in greater detail, and assessing performance across diverse food matrices to further expand the industrial applicability of fish-derived gelatin.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	S.T.	G.Ö.
C	80	20
D	80	20
DCP	60	40
DAI	60	40
L	50	50
W	50	50
CR	60	40
SR	50	50
PM	100	0
FA	100	0

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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