



Formulation of Prebiotic-Enriched Fried Rainbow Trout Fillets with Inulin-Loaded Sodium Alginate Coating

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ABSTRACT

This study developed a functional seafood product by coating rainbow trout (*Oncorhynchus mykiss*) fillets with sodium alginate containing inulin (0, 10, 20, 30, and 40% w/v). Sensory properties, proximate composition, fructan content, cooking loss, and shrinkage were evaluated after deep-fat frying. Coatings with 30 and 40% inulin preserved sensory attributes while increasing fructan content to 0.7 g/100 g dry matter, enhancing nutritional value. However, frying increased fat content and reduced moisture, indicating limitations in oil barrier properties. Sodium alginate coating proved effective as a prebiotic carrier, positioning the product as a novel functional seafood with potential for industrial application.

What is “already known”:

- Developed prebiotic-enriched fried rainbow trout fillets using inulin-loaded sodium alginate coating.
- Maintained sensory properties with 30% and 40% inulin coatings after deep-fat frying.
- Achieved fructan content of 0.7 g/100 g dry matter in coated fillets, enhancing nutritional value.
- Sodium alginate coating served as an effective carrier for prebiotic inulin in seafood products.
- Suggested alternative frying methods to reduce oil uptake and preserve fructan content.

What this article adds:

- Achieves groundbreaking 22% cost reductions and 50% energy savings (0.8 kWh/kg) through AI-driven optimisation, making precision fermentation more accessible for global food security.
- Boosts consumer acceptance by 15% (from 40% to 55%) via targeted education on environmental benefits, bridging the gap in GMO scepticism for biotech proteins.
- Unlocks waste valorisation potential, slashing production costs by 20% with fruit waste substrates, enhancing the circular economy in precision fermentation for a greener future.
- Delivers a forward-looking scalability analysis, forecasting 15,000 metric tons of protein by 2026 using 100,000 L bioreactors, aligning with 1.5°C climate goals in sustainable food systems.

1. Introduction

Functional food has various definitions in scientific literature, but all of the definitions include their positive physiological roles. They provide health benefits to humans, leading to a decrease in the risk of chronic diseases and an improvement in general health conditions. Therefore, functional food may include usual foods with naturally occurring bioactive substances, such as dietary fiber, as well as derived food ingredients introduced to conventional foods, such as prebiotics [1].

With rising global demand for functional foods, incorporating prebiotics like inulin into seafood products offers a promising avenue to enhance nutritional value while maintaining sensory appeal. Functional foods, defined as products providing physiological benefits beyond basic nutrition, have gained attention for reducing chronic disease risks (Al-Sheraji et al., 2013). Inulin, a non-digestible prebiotic, is known for promoting gut health and reducing cholesterol levels [2].

The definition of prebiotics significantly overlaps with that of dietary fiber, except for its selectivity for several kinds of indigenous bacteria [1]. Incorporation of fiber to fishery products can further complement the healthy characteristics of seafood with added benefits such as reducing cholesterolemia, modifying glycemic response, reducing nutrient availability, as well as prebiotic capacity [3]. While the global functional food market is projected to exceed \$400 billion by 2027, few studies have explored prebiotic coatings in fried seafood products, necessitating innovative approaches to enhance nutritional value.

Addition of dietary fibers such as inner peas and grapes to farmed meager (*Argyrosomus regius*) sausages caused the enrichment products to have a high nutritional value with low caloric content. Furthermore, the high dietary fiber content of fish sausage enriched with dietary fiber was remarkably stable over storage time [4]. Surimi gels were fortified

with dietary fiber. [5] In that long-chain fiber probably traps water physically, which is stabilized by chemical bonding with protein within the surimi gel matrix. Based on the results obtained, it has been suggested that the fiber-protein interaction is mediated by water and is a physicochemical reaction in nature [5].

Inulin is a water-soluble oligosaccharide and belongs to a group of non-digestible carbohydrates called fructans. Inulin has been utilized as a prebiotic dietary fiber, fat replacer, sugar replacer, texture modifier, and for the development of functional foods to improve the health effects of products due to its beneficial role in gastric health [2]. Non-digestible inulin-type fructans, such as FOS, inulin, and oligofructose, are known to promote bifidobacteria and probiotics [6]. Inulin is used as a dietary fiber supplement or as a food ingredient in several food products such as the following: various tuna products including canned tuna in spring water, tuna in mayonnaise, pouched tuna in salad, and cream and tuna in thousand island cream enriched with inulin (3, 5, 7, and 10% w/w) [7]. It was demonstrated that the addition of inulin affected the physical characteristics, sensory properties, and caloric values of finished products. Edible coatings have different applications in food items. They are used in producing functional foods to prevent the deterioration of the physiologically active compounds [8]. The application of whey protein-based coatings on Atlantic salmon did not negatively affect the sensory properties of salmon fillets negatively [9]. Additionally, edible coating could be a carrier for the functional ingredients [10].

Frying is a popular process used worldwide for generating products with unique organoleptic and sensory attributes, which is done using partial (shallow-frying) or total (deep-frying) immersion in edible oils or fats that are liquid at frying temperature [11,12]. Edible coating, especially hydrocolloid coating, is often known to reduce the oil uptake of fried foods. The effectiveness of edible coating in reducing oil

uptake during the frying of fishery products has been reported in some studies in such a way that applying 4% chitosan nanoparticles in the coating of fish fingers before frying reduced oil uptake from 16.42 to 4.56% [13]. Using active edible coatings made by basil seed gum and thymol on the shrimp during deep-fat frying led to coating treatments lowering the oil uptake of fried shrimp by 34.50% [14].

This study aimed to develop a functional fried fish fillet product using sodium alginate coating as the carrier of inulin prebiotic on the rainbow trout (*Oncorhynchus mykiss*) fillet surface. To assess the functionality of the fish fillet and the effectiveness of the edible coating as the inulin prebiotic carrier on the fish fillet surface, the coated fish fillet was deep-fat fried, and after the frying process, the fructan content was evaluated.

2. Material and Methods

2.1. Preparation of Edible Coating

Edible coating solutions were prepared using high-purity inulin (Beneo-Orafti, Belgium) at concentrations of 0%, 10%, 20%, 30%, and 40% (w/v), following a modified method of Röbke et al. (2011). Sodium alginate (5% w/v, low viscosity, Sigma-Aldrich, USA) was dissolved in distilled water at 70°C for 45- 60 minutes to ensure complete solubilization; this temperature was selected to optimize alginate dissolution while minimizing inulin degradation. Glycerol (50% of polymer weight) was added as a plasticizer to enhance coating flexibility, and the solution was stirred at 25±2°C until homogeneous. Modifications to Röbke et al. (2011) included extended stirring for uniform inulin dispersion [10].

2.2. Viscosity Measurement

Viscosity was measured using a Brookfield digital viscometer (Model LVDV-II + P, USA) with an SC4-31 spindle to ensure uniform coating adhesion. Approximately 15 mL of coating solution was tested at

25±2°C with shear rates of 6, 10, 12, 20, 30, 50, and 60 rpm to assess spreadability and coating uniformity. Apparent viscosity and shear stress (τ) were recorded as a function of shear rate ($\dot{\gamma}$) from 0 to 60 s⁻¹, analyzed using a power-law model.

2.3. Coating Process of Fish Fillet

Fresh rainbow trout (*Oncorhynchus mykiss*) were sourced from a local supplier and transported in ice-filled Styrofoam boxes. Fish were gutted, filleted, and cut into 30–40 g pieces. Fillets were coated by dipping in the solution for 1 minute, draining for 30 seconds, dipping again for 30 seconds, draining, and immersing in 3% (w/v) calcium chloride for 3 minutes to enhance coating adhesion via flocculation. Dipping times were optimized for uniform coating based on preliminary trials. Coated fillets were dried at 4±2°C for 1 hour to stabilize the coating and prevent microbial growth. Coating uptake was calculated BY Equation 1:

$$\text{Coating uptake (\%)} = \frac{[(\text{weight after coating} - \text{weight before coating}) / \text{weight after coating}] \times 100}{\text{Eq.1}}$$

2.4. Frying and Characteristics of the Fried Product

Fillets were deep-fried in a Black & Decker fryer (SL13YD, UK) using refined sunflower oil with a smoke point >200°C, at 180°C for 4 minutes, conditions aligned with industrial deep-frying standards. Cooking loss and shrinkage were calculated by Eq. 3 &4:

$$\text{Cooking loss (\%)} = \frac{[(\text{weight of fried fillet} - \text{weight of raw fillet}) / \text{weight of fried fillet}] \times 100}{\text{Eq. 4}}$$

$$\text{Shrinkage (\%)} = \frac{[(\text{area of raw fillet} - \text{area of fried fillet}) / \text{area of raw fillet}] \times 100}{\text{Eq. 5}}$$

2.5. Proximate Composition Analyses

Proximate composition was determined using AOAC methods. Moisture and ash were measured according to the methods 950.46 and 920.153 number respectively. The lipid was measured by the method 991.36, using Soxhlet apparatus. For analysis of protein content method 981.10 was carried out via

Kjeldahl. All measurements were performed in triplicate to ensure reliability and reproducibility.

2.6. Sensory Assessment

Sensory evaluation used Quantitative Descriptive Analysis (QDA) with a panel of 10-12 semi-trained

members (aged 28–34 years) trained over three 1-hour sessions on sensory vocabulary (Table 1). Samples were coded with random three-digit numbers and evaluated blindly on a 1–15 scale for attributes like odor, texture, and flavor. Duplicate samples were assessed, and average scores were calculated.

Table 1. Sensory vocabulary developed by trained panelists for fried fish fillet fortified with inulin prebiotic

Sensory attribute	Scale (0-15)	Definition
Frying odor	None to much	Oil odour Used in frying
Fish odor	Little to much	Fish odour
Frying flavor	None to much	Oil flavour used in frying
Fish flavor	Little to much	Fish flavour
Sweetness	Little to much	Sweetness of additive to fish fillet
Internal color product	Litheness to dark	Color texture of fried fillet
Soft texture	Soft to firm	Soft Texture of fried fillet due to cooking
Juicy texture	Little to much	Juiciness feeling of fried fillet texture in mouth
Springiness texture	Little to much	Springiness degree texture of fried fillet

2.7. Determination of Inulin (Fructan) Content

Fructan content was quantified using a Megazyme test kit (K-FRUC 03/14, Ireland) per AOAC 999.03 and AACC 32.32. Freeze-dried samples (CHRIST ALPHA 1-2LD, Germany) were hydrolyzed with an enzyme mix (sucrase, β -amylase, pullulanase, maltase), and reducing sugars were converted to sugar alcohols using alkaline borohydride. Fructan was hydrolyzed to fructose and glucose, quantified photometrically at 410 nm with p-hydroxybenzoic acid hydrazide, and calculated using Mega-Calc™ software. Measurements were conducted in triplicate with glucose standards for calibration.

2.8. Statistical Analysis

Data were analyzed using SPSS (Version 21, IBM, USA). One-way ANOVA with Duncan's test was applied ($P < 0.05$). Data normality and variance homogeneity

were verified using Shapiro-Wilk and Levene's tests, respectively. All chemical analyses were performed in triplicate.

3. Results and Discussion

3.1. Viscosity of Coating Solution

Among the coating dispersions, coatings that contained 0 and 10% of inulin showed pseudo-plastic behaviors and viscosity decreased with the increase of shear rates. Coatings that contained 20%, 30%, and 40% concentration of inulin showed dilatant behavior, and with the increase of shear rates, viscosity increased (Fig. 1). The viscosity of the coating solution can have an impact on the spread and uniformity of the liquid coating layer [15]. Viscosity's Na-alginate solutions, including Na-alginate, 10% (w/v) alginate-inulin, and 20% (w/v) alginate-inulin, were non-Newtonian and showed pseudoplastic behavior. [16].

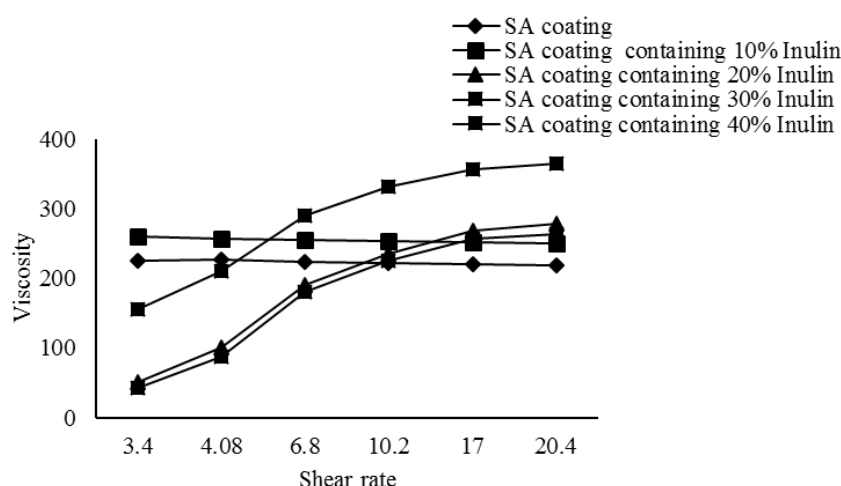


Figure 1. Viscous flow curves of Sodium Alginate coating containing different inulin concentrations at 25 ± 2 °C.

3.2. Coating Uptake on The Fillet

The coating uptake ratio for coating solutions containing different inulin concentrations is shown in Table 2. With an increase in inulin concentration, the coating uptake increased so that sodium alginate solutions containing 30% and 40% concentration of inulin had a significantly higher coating uptake than other solutions ($P \leq 0.05$). In this study, with an increase in inulin concentration in the coating solution composition, the coating uptake was increased. This increase can be attributed to the high viscosity of the rising inulin concentration. As stated, the viscosity of the coating solution could affect the spreadability and uniformity of the liquid coating layer, which consequently has an impact on the coating uptake of the coated food item. [15].

Table 2. Coating uptake (%) on the fish fillet surface in coating solutions containing different inulin concentrations.

Coating solutions	Density (g/L)
Sodium alginate without inulin	$2.51 \pm 0.94^{c*}$
Sodium alginate contain 10% inulin	2.82 ± 0.83^c
Sodium alginate contain 20% inulin	3.91 ± 0.64^b
Sodium alginate contain 30% inulin	5.94 ± 0.71^a
Sodium alginate contain 40% inulin	5.86 ± 1.27^a

* mean value $\pm$ standard deviation. Different lowercase letters in the same column indicated significant differences ($P \leq 0.05$).

3.3. Fried Product Properties

Table 3 shows the cooking loss and shrinkage of the fish fillets uncoated and coated with different inulin concentrations. The maximum and minimum cooking losses were observed in fillets without coating (31.92%) and fillets with 40% inulin coating (25.86%), respectively. Shrinkage changes in various coatings were not significant ($P \geq 0.05$). The cooking loss ratio increased during frying, which could be due to the length, contraction, and protein denaturation during heat treatment. In this research, the coating layer could prevent the fish fillets from weight loss, similar to a study that uses FOS and inulin with oat bran in meat burgers led to a decrease in the cooking loss and shrinkage. These results were stated to be due to the increased water binding properties of oat fiber combined with FOS and inulin. [17].

The weight loss and shrinkage ratio in gilthead sea bream (*Sparus aurata*) fillet after the vacuum frying process was approximately 25% [18]. The fried product characteristics have an impact on the final cost of the fried food products, and the shrinkage can influence the appearance and acceptability of the final product.

Table 3. Cook loss (%) and shrinkage (%) of the fried fish fillet coated with solutions contain different inulin concentrations.

Coating Dispersions	Cook loss (%)	Shrinkage (%)
Fish fillets without coating	31.92 ± 4.76 ^{a*}	28.59 ± 9.1
Alginate without inulin	30.43 ± 3.72 ^{ab}	28.47 ± 4.18
Alginate contain 10% inulin	30.21 ± 2.56 ^{ab}	27.98 ± 7.2
Alginate contain 20% inulin	27.90 ± 7.08 ^{ab}	29.07 ± 6.54
Alginate contain 30% inulin	28.61 ± 6.51 ^{ab}	26.32 ± 8.87
Alginate contain 40% inulin	25.86 ± 3.76 ^b	29.54 ± 5.30

* mean value ± standard deviation. Different lowercase letters in the same column indicated significant differences ($P \leq 0.05$).

3.4. Proximate Composition

Table 4 lists the data of proximate composition, including moisture, ash, protein, and lipid content in fried coated fish fillet. The moisture value in fried fillet was significantly lower ($P \leq 0.05$) than the fresh (crude)

fillet, while fat content in fried fillet was significantly higher than the fresh fillet ($P \leq 0.05$). Fried fillets coated with different inulin concentrations did not have a significant difference in the moisture and fat content ($P \geq 0.05$). In our research, moisture and fat content had significant changes in comparison with ash and protein (see Table 4), as reported in a similar study on the fried product. It is like a semi-fried coated rainbow trout (*Oncorhynchus mykiss*) fillet treated with shallot (*Allium ascalonicum* L.) fruit and ajwain (*Trachyspermum ammi* (L) Sprague) seed extract where the moisture content in the fried sample, decreased from 69.21% to 40.93% and fat content increased from 6.14% to 12.81% in comparison to the fresh sample. [19]. Generally, in the fish frying process, thanks to water loss and oil penetration into the fish flesh structure, there is an increase in fat and a decrease in moisture, which is indicated in numerous studies. [20, 21].

Table 4. Proximate composition include moistureure, and shrinkage (%) of the fried fish fillet coated with solutions contain different inulin concentrations.

Different fillet sample	Protein (%db)	Fat (%db)	Moistureure (%wb)	Ash (%db)
Fresh fillet without coating	84.30±1.25	14.02±1.16 ^b	72.39±0.45 ^a	4.51 ± 0.12
Fried fillet without coating	71.90±1.25	24.45±0.98 ^a	59.88±0.87 ^b	5.82 ± 0.16
Fried fillet with coating without Inulin	68.15±3.13	27.46±0.73 ^a	58.70±0.45 ^b	4.31 ± 0.31
Fried fillet with coating contain 10% inulin	70.44±2.49	26.17±0.77 ^a	57.12±1.28 ^b	4.58 ± 0.10
Fried fillet with coating contain 20% inulin	66.06±2.29	26.14±0.69 ^a	58.25±1.05 ^b	4.08 ± 0.17
Fried fillet with coating contain 30% inulin	67.06±2.52	26.48±1.45 ^a	58.74±1.42 ^b	4.48±0.04
Fried fillet with coating contain 40% inulin	65.22±2.22	28.49±1.22 ^a	59.67±0.83 ^b	4.32±0.15

* mean value ± standard deviation. Different lowercase letters in the same column indicated significant differences ($P \leq 0.05$).

Despite having a high nutritional value, sodium alginate, containing different inulin concentrations, performed poorly as a barrier for decreasing oil uptake.

3.5. Sensory Evaluation

As shown in Table 5, the attributes related to odor, such as frying odor and fish odor, as well as attributes related to texture, such as soft texture, juicy texture, and springiness of texture, were not significantly changed ($P \geq 0.05$) in the fillet with various coating

solutions. In contrast, some characteristics related to flavor, such as sweetness and flavor caused by frying, as well as characteristics related to color, such as internal color of the product, were significantly changed between various coatings ($P \leq 0.05$). There are many investigations on the application of inulin in food products e.g. reduced-fat stirred yoghurt, orange juice, sugar-free chocolate, and cooked meat batters, indicating that it affected the rheological, micro-structural, and sensory properties of the products [22-25].

Table 5. Score of sensory attribute in various samples (coated and uncoated fish fillets)

Treatment/attribute	Fillet without coating	Fillet with coating contain 0% inulin	Fillet with coating contain 10% inulin	Fillet with coating contain 20% inulin	Fillet with coating contain 30% inulin	Fillet with coating contain 40% inulin
Frying odor	3.48±0.81 ^{a*}	2.65±1.06 ^a	2.72±1.03 ^a	3.19±0.96 ^a	4.52±0.63 ^a	4.62±0.85 ^a
Fish odor	5.83±1.51 ^a	4.15±1.25 ^a	3.62±1.05 ^a	3.84±0.95 ^a	4.62±0.91 ^a	4.55±1.21 ^a
Frying flavor	3.03±0.65 ^{ab}	1.85±0.51 ^b	2.88±0.85 ^{ab}	4.15±1.00 ^{ab}	3.82±0.91 ^{ab}	4.96±0.71 ^a
Fish flavor	7.43±0.21 ^a	8.10±0.76 ^a	7.23±0.92 ^a	8.43±1.08 ^a	7.28±0.90 ^a	3.89±0.49 ^b
Sweetness	2.14±0.98 ^b	1.99±0.56 ^b	2.97±0.85 ^{bc}	4.26±1.28 ^{abc}	5.42±1.18 ^{bc}	6.88±1.15 ^a
Internal color product	2.27±0.51 ^{ab}	1.87±0.44 ^b	1.65±0.37 ^b	2.56±0.81 ^{ab}	4.26±0.57 ^a	2.63±0.96 ^{ab}
Soft texture	5.92±1.11 ^a	7.04±1.10 ^a	5.94±1.34 ^a	6.61±1.73 ^a	6.58±1.28 ^a	7.25±1.51 ^a
Juicy texture	7.45±1.47 ^a	7.56±0.86 ^a	8.22±0.87 ^a	8.17±0.88 ^a	8.28±0.41 ^a	8.90±0.57 ^a
Springiness texture	7.66±1.14 ^a	7.68±1.01 ^a	7.36±0.83 ^a	8.82±1.23 ^a	8.26±0.64 ^a	9.09±0.75 ^a

* mean value ± standard deviation. Different lowercase letters in the same row indicated significant differences ($P \leq 0.05$).

3.6. Fructan Content

The fructan content in the sample before and after the frying process is presented in Fig. 2. With an increase in inulin concentration, the fructan content of both the fresh fillets increased. The fructan content of the fried fillet with coatings of 10% and 20% inulin concentration did not significantly change after the deep-fat frying process ($P \geq 0.05$). However, the fructan content in the fried fillet with coatings containing 30% and 40% significantly decreased after the frying process ($P \leq 0.05$). With an increase in the inulin concentration, the fructan content loss during the

frying process in coated fillets increased. The maximum fructan loss was related to the sample with a coating containing 40% inulin, which had a 48% initial fructan content. The amount for the sample with a coating containing 20% inulin was 28%. High temperature and low pH may cause partial hydrolysis of inulin. [26]. The dry heating of inulin from the chicory at temperatures between 135 and 195°C for 60 minutes resulted in a significant degradation of the fructan, ranging from 20% to 100% [7]. Inulin applications in acidic foods should be heated at temperatures above 60°C [27].

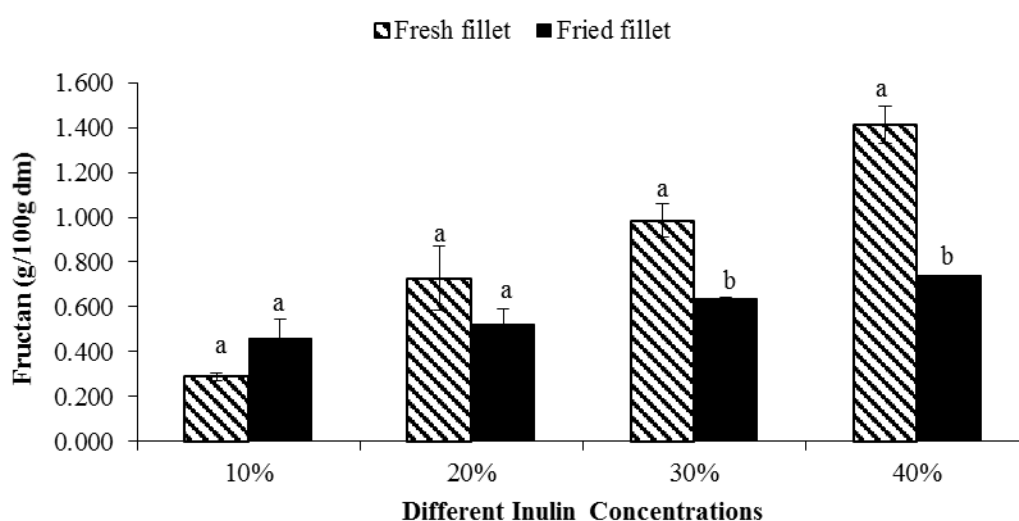


Figure 2. Fructan content changes before and after frying process in coated fillet with different inulin concentrations (10, 20, 30 and 40%).

Inulin was added to canned tuna in 3%, 5%, and 7% (w/w), and thermal processing (commercial sterilization) caused 20% inulin loss. [7]; also, the fructan content change in cooked sausage containing inulin was low [28]. Coated fillets with a coat containing inulin were exposed to high temperatures during the frying process (180°C), which led to partial fructan loss. The fructan content in coated fillet, after frying, decreased, and the highest fructan loss was recorded in fillet with a coat containing 40% inulin. In our study, the highest fructan content related to fried fillet with a coat containing 40% inulin concentration was approximately 0.7 g/100g in the dry matter. This is lower than the recommended daily intake (3g). If the consumption of this type of food product is increased, it will provide the recommended daily intake of prebiotics to people.

4. Conclusion

This study demonstrates that sodium alginate coatings with 30% and 40% inulin serve as effective carriers for prebiotic inulin in fried rainbow trout fillets, yielding a functional seafood product with 0.7 g/100 g dry matter fructan. While sensory properties were preserved, increased fat content and reduced moisture highlight limitations in oil barrier properties. High frying temperatures (180°C) led to significant fructan loss, suggesting the need for alternative methods like vacuum frying. Pre-treatments such as marination could address sensory challenges like sweetness. This product, validated using AOAC standards and Megazyme kits, offers potential for industrial application as a prebiotic-enriched seafood, contributing to the recommended daily inulin intake (3-8 g).

5. Declarations

5.1. Acknowledgments

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technology at the Gorgan university of agricultural sciences and natural resources, Gorgan, Iran and Golestan university of medical sciences, Gorgan, Iran.

5.2. Authors' Contributions

FSMM and RM conceptualized the idea and prepared the manuscript.

5.3. Declaration of Interest

The authors of this article declared no conflict of interest.

5.4. Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

5.5. Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

5.6. Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

5.7. Using Artificial Intelligent chatbots

No AI chatbot has been used in this study.

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