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# Seaweed *Pelvetia canaliculata* as a Source of Bioactive Compounds for Application in Fried Pre-Coated Mackerel (*Scomber scombrus*) Fillets: A Functional Food Approach

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**Abstract**

Fatty fish, such as mackerel (*Scomber scombrus*), are recommended as part of a healthy diet, providing essential fatty acids (FA). Fried fish is appreciated for its attributes, including a crispy texture, golden crust, and pleasant taste. However, frying increases the fat content and the caloric value of food. This study evaluated the use of pre-frying edible coatings on mackerel fillets aiming to: (i) reduce oil absorption, (ii) minimize water loss, preserving fish succulence, and (iii) prevent fat oxidation. For this purpose, alginate- and carrageenan-based coatings were supplemented with extracts of *Pelvetia canaliculata* (Pc), a seaweed with high potential as a source of bioactive compounds. The fried fillets were analysed for colour, texture, moisture, ash, lipid content, and FA profile. No significant differences were observed for colour and textural parameters. Fillets coated with Pc-supplemented carrageenan showed the highest moisture (an increase of 3%) and the lowest fat content (a decrease of 7,5%) compared to the control (fried uncoated fillets). Coated fillets also exhibited reduced saturated FA and increased monounsaturated FA. In general, linoleic acid (C18:2) decreased markedly, while the values for docosahexaenoic acid (C22:6, n-3) remained stable (11–12% of total FA). Moreover, the n3/n6 ratio and atherogenic indices (AI) were improved in the coated fillets.

**Keywords:** alginate; carrageenan; edible coatings; frying; mackerel (*Scomber scombrus*); *Pelvetia canaliculata*



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## 1. Introduction

Fish is considered a highly nutritious food, standing out for its diversity of compounds with high biological value. This staple food is an important source of energy, high-quality proteins, polyunsaturated fatty acids (PUFA), vitamins (A, B12, D, and E), and minerals (Mg, P, F, Se, Fe, Cu, Zn, I, Ca, K), accounting for about 17% of animal protein intake worldwide and up to 50% in coastal populations [1–4]. Fatty fish species are particularly rich in n-3 long-chain PUFA, such as eicosapentaenoic acid (C20:5, EPA) and docosahexaenoic acid (C22:6, DHA), which are essential fatty acids (FA) with health-promoting benefits, particularly in preventing cardiovascular diseases [5,6]. Mackerel (*Scomber scombrus*), a fatty fish abundant in the North Atlantic, is among the most frequently caught species in Portugal, along with sardine (*Sardina pilchardus*) and horse mackerel (*Trachurus trachurus*). According to PORDATA, the average annual fish capture over the past five years was 23,653 tons for mackerel, comparable to values reported for sardine (24,510 tons) and clearly higher

than those of horse mackerel (15,826 tons) [7]. Nevertheless, despite its nutritional value, mackerel remains underestimated by consumers. It is, therefore, important to promote the valorization of this marine resource and to encourage its wider consumption.

Mackerel, like many other fish species, can be cooked in a variety of ways, such as boiling, frying, roasting, steaming, and grilling. It can also be consumed raw as sashimi [8]. Frying is a widely used method for food preparation, preferred for its simplicity and appealing sensory properties [9]. Deep frying involves immersing food in oil (at 150–190 °C), which imparts unique characteristics to the final product, such as a crispy surface, a soft and juicy interior, and an appealing characteristic flavor [10]. During frying, various chemical reactions occur due to the presence of oxygen, moisture, and high oil temperatures [11,12]. Oxidation is a major concern, as it significantly reduces the nutritional value of foods. In particular, the low thermal stability of PUFA, such as linoleic acid (C18:2), linolenic acid (C18:3), EPA, and DHA, can contribute to this nutritional loss [11]. Additionally, frying by immersion increases the fat content of food matrices, altering their fatty acid profile. This change can lead to harmful effects on consumer health, particularly due to the increased intake of saturated and trans-fatty acids [13].

In recent years, various strategies have been explored to reduce oxidation and oil absorption in foods during frying, with particular attention given to the development of edible coatings [14].

An edible coating is defined as a thin layer of edible material (typically composed of proteins, polysaccharides, or lipids) applied to the surface of food products, by spraying or immersion, to improve their quality, shelf life, and appearance. These coatings do not alter the visual appeal of the product while offering protection against deterioration processes such as oxidation, moisture loss, chemical reactions, and microbial growth [15].

Beyond their functional benefits, edible coatings must also maintain desirable sensory properties and be environmentally friendly and non-polluting [16–18]. Natural polysaccharides, such as alginate and carrageenan, are widely recognized as food additives and are commonly used in the formulation of edible coatings and films to prolong the shelf life of food products. These compounds are particularly valued for their neutral taste and odor, as well as for being non-allergenic [19]. Alginate is an anionic hydrophilic heteropolysaccharide extracted from brown macroalgae (*Phaeophyta*), being among the most used polysaccharides due to its hydrocolloid behavior, emulsifying capacity, and potential nutritional benefits. Its use in coating matrices has been extensively studied [20]. For instance, Yu et al. (2019) [21] demonstrated that alginate-based coatings help maintain the quality of seafood products by inhibiting bacterial growth, retaining moisture, and reducing oxidative reactions.

Similarly, carrageenan is a well-known high molecular weight sulfated polysaccharide with gelling properties, extracted from red macroalgae (*Rhodophyta*). Its versatility makes it suitable for use both as a coating matrix and as a functional ingredient in various food formulations [22].

To enhance the oxidative stability of coated food products, antioxidant agents can be incorporated into edible coatings, as they help delay lipid oxidation. In this context, macroalgae have attracted increasing attention as a promising source of bioactive compounds. These marine organisms are naturally rich in essential minerals, trace elements, carotenoids, polyphenols, omega-3 polyunsaturated fatty acids, essential amino acids, and complex carbohydrates, many of which exhibit antioxidant activity [23,24]. Among the various macroalgae, *Pelvetia canaliculata* (a brown seaweed native to the rocky intertidal zones of Europe) shows strong potential as a source of valuable bioactive compounds, although it is not yet widely exploited for industrial applications [25,26].

The phenolic content of *P. canaliculata* is highly influenced by its exposure to cycles of immersion/emersion in the intertidal zone. In fact, these compounds are secondary metabolites linked to multiple stress responses to abiotic (such as UV light damage and air temperature fluctuations) and biotic (e.g., grazer and pathogen attack) factors [27]. Connan et al. (2007) [28] studied the effect of both day/night and tidal cycles on the phenolic content and antioxidant activity of three brown seaweeds, among which *P. canaliculata.* Its phenolic concentration reached approximately 3% DW, being positively correlated with antioxidant capacity. Air temperature was shown to influence the phenolic content, with the highest value observed on a daytime scale. This diurnal pattern promotes phenolic production as a protective response to oxidative stress induced by sunlight during low tide.

Based on this promising potential, the present study focused on the development of edible coatings enriched with *Pelvetia canaliculata* extracts for application on mackerel fillets (*Scomber scombrus*) prior to frying, with the aim of reducing fat absorption and minimizing both water loss and oxidative degradation during the cooking process. To evaluate the effectiveness of the coatings, several physicochemical parameters (namely, colour, total fat content, and fatty acid profile) were analyzed in the fried fillets, providing insight into their impact on the product's nutritional quality and oxidative stability.

## 2. Materials and Methods

### 2.1. Biological Material

The macroalga *Pelvetia canaliculata* (phylum Phaeophyta), hereafter indicated as *P. canaliculata*, was harvested in June 2019 from the beach of Pedras do Corgo, Portugal (41°14′55.52″ N, 8°43′29.89″ W). The seaweed material was carefully cleaned to remove any extraneous matter, washed with distilled water, freeze-dried, and ground into a powder.

Frozen mackerel (*Scomber scombrus*) fillets were supplied by Francisco Baratizo Lda. (Peniche, Portugal). Sunflower oil was provided by Sovena Portugal—Consumer Goods S.A. (Barreiro, Portugal).

### 2.2. Chemicals

Chemicals used in this work were obtained from several commercial suppliers, namely: sodium alginate (VWR Chemicals, Radnor, PA, USA); iota-carrageenan (Alfa Aesar, Thermo Scientific Chemicals, Waltham, MA, USA); glycerol (VWR Chemicals, Radnor, PA, USA); Tween 80 (VWR Chemicals, Radnor, PA, USA); sodium carbonate (Sigma-Aldrich, Saint Louis, MO, USA); Gallic acid (Sigma-Aldrich, Saint Louis, MO, USA); 6-hydroxy-2,5,7,8-tetramethyl-3,4-dihydrochromene-2-carboxylic acid (Trolox) (Acros Organics, Bridgewater, NJ, USA); 2,2-diphenyl-1-picrylhydrazyl DPPH (AlfaAesar, Karlsruhe, Germany); Folin–Ciocalteu reagent and the analytical standards SUPELCO 37 component FAME mix, PUFA 1, and PUFA 3 (Sigma-Aldrich, Saint Louis, MO, USA). All other reagents were of analytical grade and obtained from different sources.

### 2.3. Pelvetia canaliculata Extract Preparation

Algal biomass (10 g) was extracted using either (i) water, (ii) a 1:1 mixture of water and ethanol, or (iii) ethanol, all at a 1:10 biomass-to-solvent ratio. The extraction was performed at room temperature, under stirring for 30 min. The extract solutions were then separated from the solid residue by filtration and collected into round-bottom flasks. Solvents were removed under vacuum using a rotary evaporator (Heidolph 2, LAB1ST, Shanghai, China), followed by freeze-drying (Telstar, LyoQuest-85, Terrassa, Spain). The dried aqueous, hydroethanolic, and ethanolic extracts were stored at −20 °C until further use. For the activity assays (*cf.* 2.5.), three independent solutions (1 mg/mL) of each extract were prepared.

### 2.4. Formulation of Edible Coating Solutions

Two base edible coating solutions were formulated and evaluated, one based on sodium alginate and the other on iota-carrageenan. The composition of each formulation was selected according to previously published methodologies [16,21,29,30]. The alginate-based coating was prepared by dissolving 10 g of sodium alginate in 500 mL of distilled water, under continuous stirring at 70 °C. Once the solution was cooled to room temperature, 3 g glycerol was added, followed by homogenization for an additional 30 min.

The carrageenan-based coating solution was prepared by dissolving 5 g of iota-carrageenan in 500 mL of distilled water at 80 °C under constant stirring. After cooling to room temperature, 3.75 g of glycerol and 0.1 g of Tween 80 were incorporated, and the solution was further stirred for 30 min.

Ethanolic extracts of *P. canaliculata* were added to both base solutions at concentrations of 0.1%, 0.2%, 0.5%, 0.7%, and 1% (*m*/*v*). The antioxidant activity of the resulting formulations was evaluated using the DPPH radical scavenging assay, and the total phenolic content was determined, as described in Section 2.5. The extract concentration used in each coating solution was selected based on DPPH $IC_{50}$ values (*cf.* 3.2). The final compositions of the coating solutions selected for application on mackerel fillets are presented in Table 1.

**Table 1.** Formulation of edible coating solutions tested in mackerel fillets.

| Coating Solution | Polysaccharide (% *m*/*v*) | Glycerol (% *m*/*v*) | Tween 80 (% *m*/*v*) | *P. canaliculata* EtOH Extract (% *m*/*v*) |
|---|---|---|---|---|
| Carrageenan (Car) | 1 | 0.75 | 0.02 | 0 |
| Carrageenan with *P. canaliculata* extract (Car Pc) | 1 | 0.75 | 0.02 | 1 |
| Alginate (Alg) | 2 | 0.6 | 0 | 0 |
| Alginate with *P. canaliculata* extract (Alg Pc) | 2 | 0.6 | 0 | 0.5 |

### 2.5. Evaluation of the Antioxidant Activity of Extracts and Edible Coating Solutions

#### 2.5.1. Total Phenolic Content

The total phenolic content of *P. canaliculata* extracts and coating solutions was determined using the Folin–Ciocalteu colorimetric method, as described by Neves et al. (2020) [31]. In Eppendorf tubes,10 µL of either the coating solution, extract solution (1 mg/mL) or distilled water (blank) was mixed with 840 µL of water and 50 µL of Folin–Ciocalteu reagent. The mixture was homogenized and incubated in the dark for 5 min. After this, 150 µL of a 20% (*w*/*v*) sodium carbonate solution was added, followed by further homogenization. The samples were then incubated at room temperature for 1 h. Subsequently, 200 µL of each solution was transferred, in quadruplicate, to a 96-well plate, and the absorbance was measured at 755 nm using a microplate reader (Epoch 2™, Biotek Instruments, Inc., Winooski, VT, USA). The total phenolic content was calculated by interpolation from a standard calibration curve prepared using gallic acid in concentrations ranging from 10 to 100 µg/mL. Results were expressed as µg of gallic acid equivalents (GAE) per mL of coating solution or per mg of extract.

#### 2.5.2. Radical 2,2-Diffiphenyl-1-Pylrilhydrazine (DPPH) Scavenging Activity

The antioxidant activity of *P. canaliculata* extracts and coating solutions was assessed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay, as described by Neves et al. (2021) [32]. Briefly, 10 µL aliquots of either the coating solution, extract

solution (1 mg/mL), distilled water (blank) or Trolox standard solutions (10 to 750 μg/mL), were added to 990 μL of an ethanolic DPPH solution (40 μg/mL). The mixtures were homogenized and incubated at room temperature in the dark for 30 min. Lastly, 200 μL of each reaction mixture was transferred, in quadruplicate, to a 96-well plate, and the absorbance was measured at 517 nm using a microplate reader. Antioxidant activity was expressed as Trolox equivalents (μg/mg of extract or μg/mL of coating solution). For coating solutions supplemented with *P. canaliculata* ethanolic extract, the concentration of extract required to inhibit 50% of DPPH radical activity ($IC_{50}$) was also determined and expressed as % (*m*/*v*).

#### 2.5.3. Ferric Reducing Activity Power (FRAP)

The antioxidant activity of *P. canaliculata* extracts was also evaluated by the ferric reducing activity power (FRAP) assay, as described by Neves et al. (2021) [32]. Briefly, 30 μL of either extract, solvent, or Trolox solutions (ranging from 75 to 1000 μg/mL) was mixed with 900 μL FRAP reagent (a solution composed of acetate buffer 0.3 mol/L, FeCl3 20 mmol/L and TPTZ 10 mmol/L, in a 10:1:1 ratio). After 40 min in the dark, 200 μL aliquots were transferred, in quadruplicate, to a 96-well microplate, and the absorbance of the samples was measured at 595 nm using a microplate reader. Results were expressed as Trolox equivalents (μg/mg extract).

### *2.6. Application of Coatings on Mackerel Fillets*

Fillets were cut, still frozen, into sections approximately 7 cm in length and about 4 cm in width, then thawed at room temperature and weighed. Thereafter, the fish fillets were submerged in the coating solution for 30 s and transferred to a plastic grille for 2 min to remove excess coating. After that, the coated fillets were frozen in a bench plate freezer (FT34MKII, Armfield, Ringwood, UK). For each coating formulation (Table 1), a total of 5 fillets were prepared. The samples were stored at -50 °C for four weeks, until frying assays were performed.

### *2.7. Frying Process*

Frying assays were carried out in a domestic fryer model DF400 (KREA Swiss AG, Tägerwilen, Switzerland) containing 3 L of sunflower oil. For each coating solution, five fillets were fried simultaneously at 165 ± 5 °C for 4 min. After frying, the fillets were placed on absorbent paper for 45 s on each side to remove excess oil. The fish fillets were then allowed to cool to room temperature. At the end of each frying batch, the oil was discarded, the fryer was properly cleaned, dried, and filled with fresh sunflower oil. Five uncoated fillets were also fried under the same conditions and used as the control.

The fried fillets were assessed for colour and textural attributes immediately after cooling. Then, the fillets were ground for moisture and ash evaluation and stored separately at −50 °C until further chemical analyses.

### *2.8. Analysis of Fried Mackerel Fillets*

#### 2.8.1. Colour Differences

Colour analysis was performed using a Konica Minolta colorimeter (CR-400, Minolta, Osaka, Japan), calibrated with a white ceramic plate provided by the manufacturer. The results obtained were analysed according to the CIELab model, which includes three coordinates, L*, a*, and b*. In this model, L* represents luminosity (similar to a greyscale), ranging from black (0%) to white (100%). Parameter a* relates to the green-red spectrum (from −60 to +60), while parameter b* (also from −60 to +60) indicates yellow when positive and blue when negative. Samples were prepared by placing the fillets in Petri dishes, and colour coordinates (L*, a* and b*) were measured on the surface using a reflectance mode

with daylight calibration (D65). To determine the total colour difference (TCD), the method described by DrLange (1994) [33] was used. This procedure compares the L*, a* and b* coordinate values of the test samples (fried coated fillets) with those of the control group (fried uncoated fillets, $L_0^*$; $a_0^*$ and $b_0^*$), using Equation (1) shown below.

$$TDC = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad \text{being } \Delta L = L^* - L_O^*;\ \Delta a = a^* - a_O^* \text{ and} \Delta b = b^* - b_O^* \quad (1)$$

2.8.2. Evaluation of Textural Attributes

For textural characterization of fried fillets, a texture analyzer (Ta.XTplusC, Stable Micro Systems, Surrey, UK), equipped with a Warner Bratzler blade probe, was used. The equipment was calibrated with a cutting speed of 5 mm/s and a compression distance of 15 mm, adapted to ensure maximum reproducibility for the samples tested. The measured attributes were distance at failure (elasticity), work of shear, and cutting strength (firmness).

2.8.3. Moisture and Ash Contents

The moisture and ash contents of fried fillets were determined as described by Antunes et al. (2023) [34]. The samples (1 g) were placed in dried crucibles and kept in an oven (FD115, Binder GmbH, Tuttlingen, Germany) at 105 °C for 48 h. After that, the samples were transferred to a desiccator to cool and then weighed repeatedly until a constant weight was reached to determine water loss. For ash quantification, the crucibles containing the dehydrated samples were placed in a muffle furnace (Nabertherm, Liliemthal/Bermen, Germany) at 525 °C for 5 h and then weighed as described above. Moisture and ash contents were expressed as a percentage of fresh weight (% FW).

2.8.4. Total Lipid Content

The quantification of total lipids of fried fillets was performed using the Folch method [35] with some modifications as described by Antunes et al. (2023) [34]. Samples (1 g) were weighed into Falcon tubes and mixed with 10 mL of Folch reagent (chloroform: methanol, 2:1 $v/v$). This mixture was homogenized for 5 min, followed by the addition of 1.2 mL of 0.8% NaCl, and further homogenized for two more min. The mixture was then centrifuged for 10 min at 6000 rpm. The lower phase (fat extract) was collected and filtered through a column of anhydrous sodium sulphate into an evaporation flask. Then, 2 mL of chloroform was added to the remaining contents of the Falcon tube, and the extraction process was repeated. Finally, the chloroform from the fat extract was removed by evaporation under vacuum. The flasks containing the lipid residue were dried at 60 °C until a constant weight was achieved. Lipid content was expressed as a percentage of the fresh sample (% FW).

2.8.5. Analysis of the Fatty Acid Profile

The analysis of the fatty acid profile of fried fillets was performed as described by Antunes et al. (2023) [34]. Fatty acid methyl esters (FAME) were obtained by direct acid transmethylation of the samples. Briefly, 50 mg of sample was mixed with 2 mL of 2% sulfuric acid in methanol and heated at 80 °C for 2 h. After cooling, 1 mL of ultrapure water and 2 mL of hexane were added. The mixture was homogenized and centrifuged for 5 min at 1500 rpm to separate the phases, and the upper fraction, containing the FAME, was transferred to vials. Gas chromatography (GC) analysis was performed in a gas chromatograph (Finnigan Ultra Trace, Thermo Fisher Scientific, Waltham, MA, USA), equipped with a Thermo Tr-FAME capillary column (60 m × 0.25 mm ID, 0.25 µm film thickness), an automatic injector (Autosampler AS 3000, Thermo Electron Corporation, Waltham, MA, USA), and a flame ionization detector (FID), under the following chromatographic conditions: Detector temperature: 280 °C; Injector temperature: 250 °C (splitless mode); Oven

temperature program: Start at 100 °C (1 min), increase at 9 °C/min to 180 °C (10 min), then increase at 2 °C/min to 235 °C (5 min). Helium (1.2 mL/min) was used as the carrier gas. Flame detector was supplied with synthetic air (350 mL/min) and hydrogen (35 mL/min). Data acquisition and analysis were performed using Xcalibur software version 1.4 (Thermo Fisher Scientific Inc., Waltham, MA, USA). Fatty acid identification was carried out by comparing the retention times of the FAMEs with those of standard mixtures: SUPELCO 37, PUFA 1, and PUFA 3. Results were expressed as a percentage of the total peak area (% total FA). Also, the Hypocholesterolemic/hypercholesterolemic (h/H), atherogenic (AI), and thrombogenic (TI) indices were calculated by application of Equations (2)–(4) [34].

$$h/H = \frac{C18:1n9 + C18:1n7 + C18:2n6 + C18:3n6 + C18:3n3 + C20:3n6 + C20:4n6 + C20:5n3 + C22:4n6 + C22:5n3 + C22:6n3}{C14:0 + C16:0} \quad (2)$$

$$AI = \frac{C12:0 + 4 \times (C14:0) + C16:0}{MUFA + n3 + n6} \quad (3)$$

$$TI = \frac{C14:0 + C16:0 + C18:0}{0.5 \times MUFA + 3 \times n3 + 0.5 \times n6 + n3/n6} \quad (4)$$

2.8.6. Statistical Analysis

All experiments were carried out in three independent replicates, and the values presented correspond to mean ± standard deviation. Statistical analyses were performed using SPSS software 25 (IBM Corporation, Armonk, NY, USA), with the significance level set at $p \leq 0.05$. The data were analysed by one—way analysis of variance (ANOVA), followed by Tukey's post hoc test. ANOVA assumptions were assessed using the Kolmogorov–Smirnov for normality and Levene's test for homogeneity of variances. When assumptions were not met, the Kruskal–Wallis nonparametric test was applied. Principal component analysis (PCA) was performed using CANOCO 4.5 software to identify the main sources of variation between samples, concerning nutritional parameters and healthy fatty acid indices. PCA was applied to the log-transformed dataset of all analyses.

## 3. Results and Discussion

### *3.1. P. canaliculata Extracts: Total Phenolic Content and Antioxidant Activity Evaluation*

In this study, food-grade solvents (water and ethanol) were used to obtain *P. canaliculata* extracts suitable for incorporation into edible coatings. Extraction with water and with a water:ethanol mixture (1:1) produced similar yield values (28.6 and 25.3% DW, respectively), which were approximately three times higher than the yield obtained with ethanol (9.0%). The aqueous, hydroethanolic (1:1), and ethanolic extracts of *P. canaliculata* were evaluated for total phenolic content (TPC) and antioxidant activity using the DPPH and FRAP methods (Table 2).

**Table 2.** Total phenolic content (TPC) and antioxidant activity evaluated by the DPPH and FRAP methods of aqueous, hydroethanolic (1:1) and ethanolic extracts of *P. canaliculata*. For each method (same row), same letter means significant differences ($p < 0.05$) between extracts.

| ***P. canaliculata* Extract** | **$H_2O$** | **EtOH:$H_2O$** | **EtOH** |
|---|---|---|---|
| TPC (μg GA/mg) | 48.7 ± 9.1 [a] | 55.4 ± 3.7 [b] | 203 ± 32 [a,b] |
| DPPH (μg Trolox/mg) | 38.3 ± 3.8 [a] | 39.9 ± 2.9 [b] | 180.7 ± 7.4 [a,b] |
| FRAP (μg Trolox/mg) | 15.8 ± 2.5 [a] | 16.2 ± 2.1 [b] | 55.3 ± 4.7 [a,b] |

The ethanolic extract exhibited the highest TPC (203 ± 32 μg GA/mg) and the strongest activity in both the DPPH (180.7 ± 7.4 μg Trolox/mg) and FRAP (55.37 ± 4.7 μg Trolox/mg)

assays. Aqueous and hydroethanolic extracts showed similar activities, with TPC, DPPH and FRAP values clearly below those of the ethanolic extract. Moreover, a strong positive correlation was observed between TPC and antioxidant activity of all extracts, suggesting the importance of phenolic compounds as antioxidant agents. These results indicate higher efficiency of ethanol in selectively extracting antioxidant compounds. For this reason, ethanolic extract was selected for incorporation into coating solutions applied to mackerel fillets.

The antioxidant activity of this seaweed has been reported by other authors, mostly attributed to phenolic compounds. Sousa et al. (2021) [26] characterized methanolic extracts from the same biomass used in this study and reported TPC, FRAP and DPPH values lower than those of the ethanolic extract but higher than those of the aqueous and hydroethanolic extracts. Similarly, O'Sullivan et al. (2011) [36] reported considerably lower TPC in methanolic extracts of *P. canaliculata* from Ireland, along with weaker antioxidant activity. On the other hand, Tierney et al. (2013) [37] tested several extraction conditions for *P. canaliculata* from Ireland and described antioxidant activities consistent with the values obtained in this study, noting that cold water or 80% ethanol extractions led to better results than hot water as the extraction solvent.

### 3.2. Characterization of Edible Coating Solutions

Carrageenan and alginate coating solutions, prepared as described in Section 2.4, were supplemented with *P. canaliculata* ethanolic extract at concentrations ranging from 0% to 1% (*m*/*v*), resulting in a total of 12 solutions. Each solution was then characterized for total phenolic content and antioxidant activity by the DPPH method (Figure 1). These assays aimed to evaluate the effect of the binomial extract-polysaccharide on the coating solution properties.

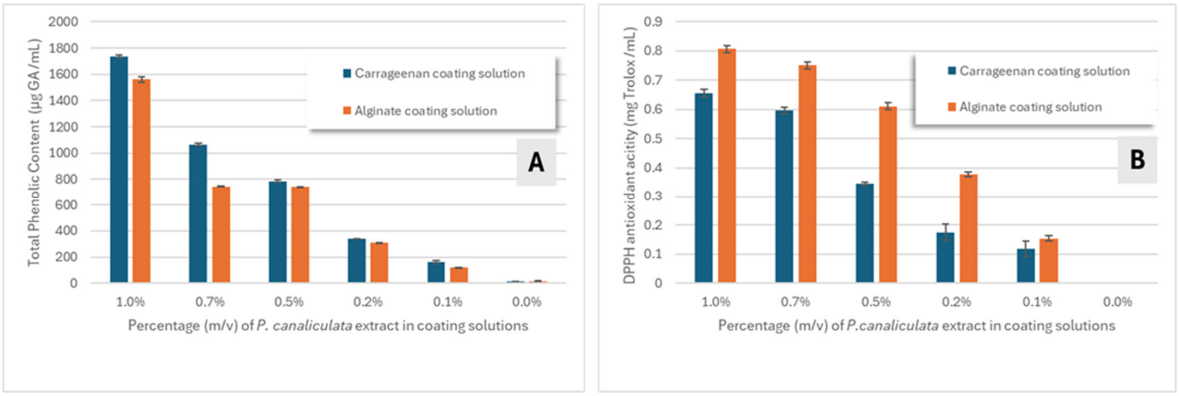


**Figure 1.** (**A**) Total phenolic content and (**B**) DPPH antioxidant activity of carrageenan and alginate coating solutions supplemented with ethanolic extract of *P. canaliculata* at concentrations ranging from 0% to 1%.

In general, an increase in phenolic content (Figure 1A) and antioxidant activity (Figure 1B) was observed with increasing *P. canaliculata* extract concentration in both carrageenan and alginate coating solutions. Moreover, coating solutions without extract addition (0%) showed no antioxidant activity or phenolic content. However, some differences between the two base coating solutions were detected. Analysing the results of the DPPH assays, it was evident that alginate-based solutions consistently presented higher antioxidant activity compared to carrageenan solutions at the same extract concentration. Carrageenan with 1% extract achieved an antioxidant activity of 0.66 ± 0.01 mg Trolox per mL, which was clearly lower than alginate with the same extract concentration (0.81 ± 0.01 mg/mL) and similar to the value for alginate with 0.5% extract (0.61 ± 0.1% mg/mL). This differ-

ence between the two base solutions is further supported by the IC50 values, the extract concentration capable of inhibiting 50% of the DPPH radical, which were 0.96% and 0.50% for carrageenan and alginate base solutions, respectively. However, this difference was not observed in the total phenolic content results, as the highest TPC values were found in carrageenan solutions.

These results may be explained based on the distinct bounds that are established between polysaccharide coatings and the phenolic compound from the extracts, which potentially affects their reactivity in both DPPH and Folin assays. In fact, only the free hydroxyl groups are able to undergo redox reactions, being detected in the Folin–Ciocalteu assay [38,39]. Also, the results of the DPPH method, which measures the free radical scavenging ability of antioxidants, can be influenced by several factors attributed to polysaccharide matrices. In fact, physical entrapment of antioxidants and the barrier effect of matrices, as well as their interference with the solubility or dispersion of phenolic compounds, have been reported [40]. However, a more insightful explanation for the observed differences would require a detailed analysis of the phenolic profile of the algae extract.

Aiming to select the appropriate extract concentration to apply in both base coating solutions for frying assays, a compromise strategy was adopted. Although increasing the extract concentration resulted in higher DPPH and TPC values, it also adversely affected the rheological properties of the coating solution, namely its viscosity and, consequently, its adhesion to the food matrix. Therefore, the extract concentration corresponding to the DPPH $IC_{50}$ value was selected, i.e., 1% for carrageenan-based and 0.5% for alginate-based coatings (Table 1).

### *3.3. Characterization of Fried Mackerel Fillets*

Fried mackerel fillets were characterized concerning colour and textural attributes as well as their nutritional composition, namely moisture, ash, total fat content and fatty acid profile.

#### 3.3.1. Colour Evaluation

Colour is an important quality attribute that plays a key role in consumer acceptability, influencing their perception of ripeness, freshness and even nutritional content.

Figure 2A shows the results obtained for the colour parameters of the CIELab model (L*, a* and b*), with no statistically significant differences observed between samples. Fillets coated with alginate solution supplemented with *P. canaliculata* extract (Alg Pc) exhibited the lowest luminosity value (L* = 49.6 ± 6.8). Conversely, the highest value (L* = 60.9 ± 3.4) was observed in fillets coated with carrageenan (Car).

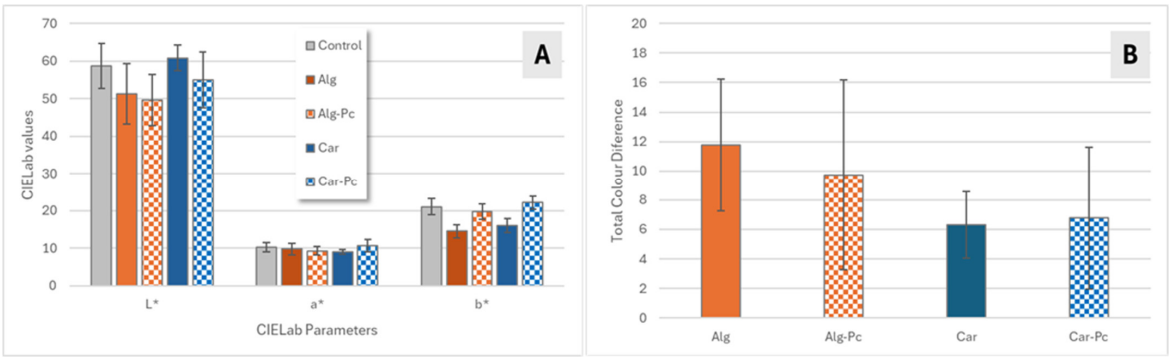


**Figure 2.** CIELab parameters (**A**) and total colour difference (**B**) of fried mackerel fillets. Uncoated fried fillets (Control); fillets coated with alginate solution (Alg); fillets coated with alginate solution supplemented with *P. canaliculata* (Alg Pc); fillets coated with carrageenan solution (Car); fillets coated with carrageenan solution supplemented with *P. canaliculata* (Car Pc).

However, these differences were not noticeable through visual observation (Figure 3).

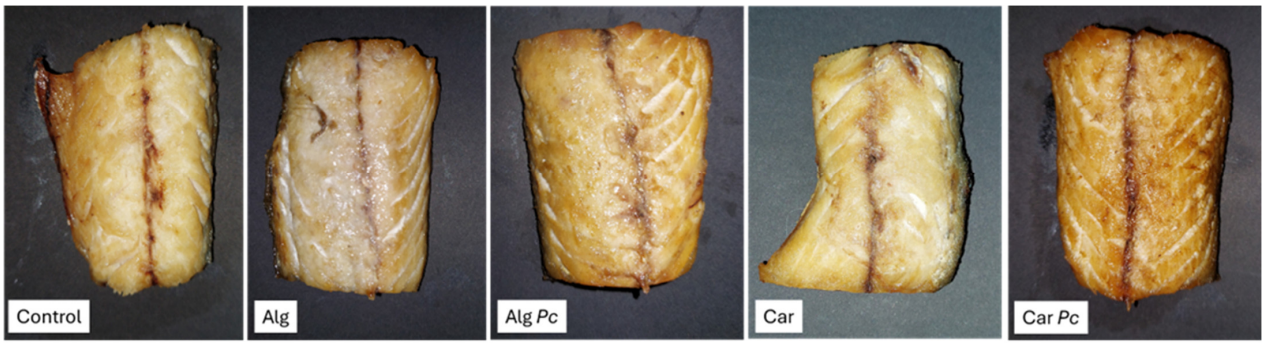


**Figure 3.** Visual appearance of fried mackerel fillets. Uncoated fried fillets (Control); fillets coated with alginate solution (Alg); fillets coated with alginate solution supplemented with *P. canaliculata* (Alg Pc); fillets coated with carrageenan solution (Car); fillets coated with carrageenan solution supplemented with *P. canaliculata* (Car Pc).

Regarding the a* parameter, which ranged from 9.0 ± 0.7 (Car) to 10.7 ± 1.6 (Car Pc), all samples exhibited a slight red hue, indicating that the presence of algae extract did not affect the fillets' final colour. For the b* parameter, all samples showed a tendency towards yellow, with values between 14.5 ± 1.7 (Alg) and 22.2 ± 1.8 (Car Pc). Considering that a golden yellow hue is appealing in fried foods, it can be concluded that the fillets achieved the desired appearance for the final product (Figure 3). The total colour difference between coated fried fillets and the control is presented in Figure 2B. The alginate-coated fillets (Alg and Alg Pc) exhibited the highest value, but without significant differences when compared to the carrageenan-coated samples (Car and Car Pc).

Generally, it is desirable that fried foods exhibit both higher lightness (L*) and yellowness (b*), and lower redness (a*). Frying time and temperature assume a prominent effect in these parameters, being promoters of non-enzymatic processes such as the Maillard reaction and the caramelization of sugars [41]. The browning effect caused by the Maillard reaction is due to the presence of reducing sugars (like glucose or fructose) and amino acids that react when exposed to the high temperature of frying oil. Acrylamide is a potentially harmful compound formed as a by-product of the Maillard reaction, using the amino acid asparagine as a reaction precursor. Its formation is a special concern when fish is coated in flour-based batter or breadcrumb mix, which are often rich in sugars and starch. The polysaccharide coating was shown to be effective in slowing down the Maillard reaction by retaining moisture inside the food matrix, reducing oil uptake and forming a physical barrier that limits the interaction between reducing sugars and amino acids [39].

#### 3.3.2. Textural Attributes of Fried Mackerel Fillets

Regarding the textural attributes of fried mackerel fillets, no statistically significant differences were observed between samples for any of the parameters analysed: (i) distance at failure (Figure 4A), (ii) cutting strength (Figure 4B) and (iii) work of shear (Figure 4C).

The distance at failure, which is related to the elasticity of the samples, was highest in the control sample (37.7 ± 2.1 mm), while the lowest value was observed for Car Pc (35.6 ± 1.3 mm). The cutting strength, which is correlated with the firmness of the samples, ranged from 0.95 ± 0.38 N (Car) to 1.43 ± 0.68 N (Car Pc). Concerning the work of shear, also related to firmness, the lowest value was found in the control sample (1.6 ± 1.1 N.s), whereas Car Pc exhibited the highest value (4.7 ± 1.5 N.s). For both base coating solutions, the presence of the algae extract resulted in increased firmness parameters and decreased elasticity, suggesting an overall improvement of textural attributes.

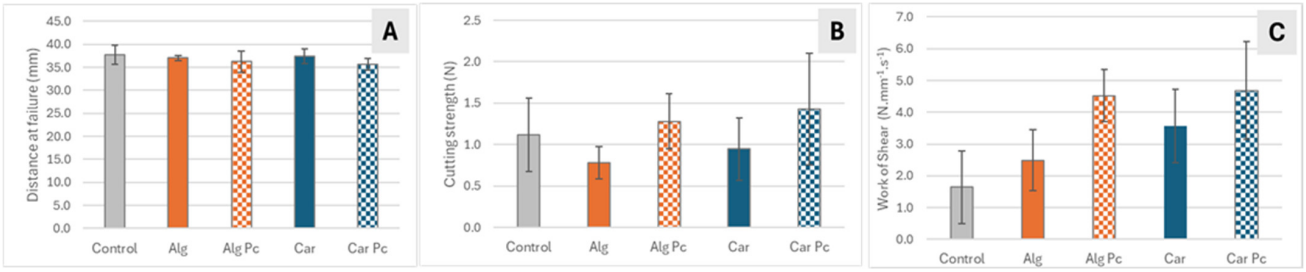


**Figure 4.** Textural attributes of fried mackerel fillets. Distance at failure (**A**), cutting strength (**B**) and work of shear (**C**). Uncoated fried fillets (Control); fillets coated with alginate solution (Alg); fillets coated with alginate solution supplemented with *P. canaliculata* (Alg Pc); fillets coated with carrageenan solution (Car); fillets coated with carrageenan solution supplemented with *P. canaliculata* (Car Pc).

### 3.3.3. Nutritional Characterization of Fried Mackerel Fillets

During frying, several factors influence the nutritional composition of the food matrix, namely its own composition (such as water content, macro- and micronutrients levels), the time/temperature combination, oil composition, namely the proportions of saturated fatty acids (SFA), monounsaturated fatty acids (MUFA) and PUFA, oil-to-food ratio, among others [42].

The application of coatings to fillets prior to frying aims to create a barrier against oil absorption and water loss. Therefore, it is expected that coated fillets will have a lower lipid content while retaining more moisture in the tissues.

The microstructure of alginate and carrageenan coatings, which is the internal network created by the polymer chains, has a key role in the barrier effect to oil and moisture. Furthermore, the addition of extracts can change the polymer interactions, modifying the microstructure and the coating functionality [43].

To evaluate the effect of the coatings, several nutritional parameters of the fried fish fillets were analyzed. Figure 5 presents the results for moisture, ash content, and total lipids.

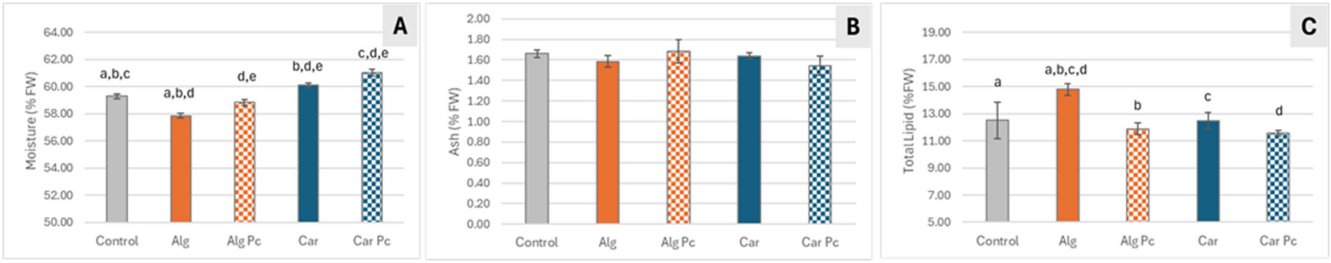


**Figure 5.** Composition of fried mackerel fillets concerning moisture (**A**); ash (**B**) and total lipid content (**C**). Uncoated fried fillets (Control); fillets coated with alginate solution (Alg); fillets coated with alginate solution supplemented with *P. canaliculata* (Alg Pc); fillets coated with carrageenan solution (Car); fillets coated with carrageenan solution supplemented with *P. canaliculata* (Car Pc). For each parameter, the same letter means significant differences ($p < 0.05$) between samples.

Carrageenan with *P. canaliculata*-coated fillets (Car Pc) showed the highest moisture content (61.04 ± 0.26%), which was significantly higher than that of Car (60.11 ± 0.17%) and control (59.29 ± 0.19%) samples. Conversely, alginate-coated fillets (Alg) stand out for the lowest moisture content (57.87 ± 0.19%). Comparing the two base coating solutions for moisture values, it may be concluded that carrageenan more efficiently preserves water within fish tissues. Additionally, the presence of algae extracts increased water content in the food matrix, as confirmed by statistical analysis, thereby enhancing the succulence of the fish fillets (Figure 5A). Chang et al. (2021) [44] found that higher values of moisture in fried

Spanish Mackerel (about 65%) resulted in improved textural attributes, characterized by lower hardness and chewiness. This conclusion sustains the results obtained for the effect of *P. canaliculata* in coated fried fillets concerning textural attributes and moisture content.

Regarding ash content, which is related to inorganic matter, no statistically significant differences were observed for all the samples analysed (Figure 5B). This parameter ranged from 1.54 ± 0.09% FW (Car Pc) to 1.68 ± 0.12% FW (Alg Pc).

Carrageenan coating solutions slightly decreased the fat content of fish fillets compared to the control sample. Moreover, the addition of algae extract improved the efficiency of both alginate and carrageenan coating solutions as oil barriers. The lowest fat content was observed in Car Pc (11.57 ± 0.19% FW) and Alg Pc (11.88 ± 0.19% FW). Conversely, alginate-coated fillets showed the highest fat content (14.79 ± 0.41% FW), with a statistically significant difference compared to the control (12.5 ± 1.3% FW).

One of the mechanisms proposed for describing oil absorption in food matrices is water replacement, which states that rapid evaporation of water during frying creates holes in the structure, which allows oil to penetrate, thus increasing its uptake [45]. This may explain the results observed in this study, where samples with higher moisture content showed lower fat absorption (Car Pc). Another explanation for oil absorption might be the increase in polar compounds during the frying process as oil degrades. These compounds act as surfactants, promoting contact between the food and the frying oil, thereby enhancing oil uptake [46]. Nevertheless, in this study, this effect might be neglected since the oil was replaced at the end of each frying batch (4 min).

Besides the slight differences observed in fat content, the fish samples exhibited markedly distinct fatty acid profiles. The fatty acid profile of the fried fillets results from both the original fish matrix and the sunflower oil absorbed during frying. Also, chemical reactions that take place along the process can provide changes in FA composition in fried samples.

The sunflower oil used in this study is predominantly composed by linoleic acid (C18:2 n-6), followed by oleic (C18:1 n-9), palmitic (C16:0), and stearic (C18:0) FA, which accounted for 59.36 ± 0.15%, 29.15 ± 0.09%, 6.71 ± 0.10%, and 3.07 ± 0.02% of total FA, respectively [31]. The high content of PUFA, particularly susceptible to oxidation, has a negative impact on the frying performance of sunflower oil. Nevertheless, this oil was selected for this study due to its widespread use in Portuguese cuisine [11].

Atlantic mackerel, classified as a fatty fish, is particularly rich in PUFA, especially the n-3 fatty acids docosahexaenoic acid (DHA, C22:6 n-3) and eicosapentaenoic acid (EPA, C20:5 n-3), with reported values ranging from 19–40% to 5–12% of total fatty acids, respectively. The most abundant saturated fatty acids are palmitic (C16:0) and stearic (C18:0), while oleic (C18:1 n-9) is the predominant monounsaturated fatty acid, typically comprising 7–14% of total FA. Other unsaturated fatty acids present include arachidonic acid (C20:4 n-6), at 3–8%, and linoleic acid (C18:2 n-6) in smaller amounts, ranging from 1 to 2.5% [47,48].

In the present study, it was observed that the most abundant saturated fatty acids in the post-frying fillets are palmitic (from 15.7 ± 1.5 to 18.30 ± 0.35%) and stearic (ranging from 5.40 ± 0.16 to 6.28 ± 0.09%), regardless of the applied coating formulation (Table 3). Statistically significant differences were observed between control and the coated fillets Alg Pc for both myristic (C14:0) and stearic fatty acids. The highest value for total saturated FA was exhibited by the control sample (31.59 ± 0.23), conversely to Alg Pc (26.9 ± 2.2), which attained a significantly lower value. It is worth mentioning that the presence of algae extract resulted in a decrease in SFA content in both base-coatings. Oleic was the most abundant fatty acid in all the samples, being higher in coated fillets (ranging from 27.14 ± 0.66%, in Alg Pc to 44.94 ± 0.95% in Car Pc) than in the control (24.56 ± 0.10%).

**Table 3.** Fatty acid (FA) profile of fried mackerel samples. Healthy fatty index: hypocholesterolemic/hypercholesterolemic (h/H), atherogenic (AI), and thrombogenic (TI). Uncoated fried fillets (Control); fillets coated with alginate solution (Alg); fillets coated with alginate solution supplemented with *P. canaliculata* (Alg Pc); fillets coated with carrageenan solution (Car); fillets coated with carrageenan solution supplemented with *P. canaliculata* (Car Pc). In rows with bold parameters, the symbol "*" means statistically significant differences between coated samples and control. nd—not detected.

| FA | Control | Alg | Alg Pc | Car | Car Pc |
|---|---|---|---|---|---|
| C12:0 | 0.08 ± 0.02 | 0.07 ± 0.02 | 0.05 ± 0.01 | 0.06 ± 0.02 | 0.07 ± 0.01 |
| C13:0 | 0.10 ± 0.01 | 0.09 ± 0.02 | 0.09 ± 0.02 | 0.11 ± 0.02 | 0.09 ± 0.01 |
| **C14.0** | 4.26 ± 0.07 * | 3.90 ± 0.09 | **3.28 ± 0.23** * | 4.25 ± 0.13 | **3.42 ± 0.12** * |
| C15:0 | 0.84 ± 0.03 | 0.84 ± 0.03 | 0.69 ± 0.06 | 0.97 ± 0.04 | 0.73 ± 0.06 |
| C16:0 | 18.30 ± 0.35 | 17.52 ± 0.11 | 15.7 ± 1.5 | 17.02 ± 0.06 | 16.09 ± 0.12 |
| C17:0 | 1.21 ± 0.03 | 1.13 ± 0.07 | 0.91 ± 0.24 | 1.58 ± 0.07 | 0.95 ± 0.21 |
| **C18:0** | 6.28 ± 0.09 | 6.06 ± 0.12 | **5.40 ± 0.16** * | 5.88 ± 0.03 | 5.96 ± 0.04 |
| C20:0 | 0.29 ± 0.10 | 0.34 ± 0.07 | 0.29 ± 0.10 | 0.30 ± 0.01 | 0.32 ± 0.04 |
| C21:0 | nd | 0.07 ± 0.02 | 0.02 ± 0.03 | 0.06 ± 0.00 | 0.07 ± 0.00 |
| C22:0 | 0.20 ± 0.04 | 0.23 ± 0.01 | 0.28 ± 0.02 | 0.25 ± 0.02 | 0.27 ± 0.03 |
| C24:0 | 0.13 ± 0.07 | 0.13 ± 0.04 | 0.13 ± 0.11 | 0.12 ± 0.01 | 0.12 ± 0.03 |
| C16:1 n-7 | 2.80 ± 0.26 | 2.91 ± 0.11 | 2.29 ± 0.26 | 3.16 ± 0.17 | 2.34 ± 0.30 |
| C17:1 n-7 | 0.74 ± 0.03 | 0.64 ± 0.12 | 0.47 ± 0.11 | 0.85 ± 0.04 | 0.57 ± 0.13 |
| *trans* C18:1 n-9 | 0.20 ± 0.07 | 0.15 ± 0.09 | 0.03 ± 0.04 | 0.27 ± 0.08 | 0.30 ± 0.17 |
| **C18:1 n-9** | 24.56 ± 0.10 * | **39.93 ± 0.54** * | 27.14 ± 0.66 | **37.49 ± 0.36** * | **44.94 ± 0.95** * |
| C20:1 n-9 | 1.40 ± 0.01 | 1.35 ± 0.02 | 0.97 ± 0.14 | 1.31 ± 0.05 | 1.27 ± 0.09 |
| C22:1 n-9 | 0.73 ± 0.27 | 0.52 ± 0.05 | 0.37 ± 0.11 | 0.64 ± 0.16 | 0.44 ± 0.06 |
| C24:1 n-9 | 0.77 ± 0.06 | 0.78 ± 0.02 | 0.84 ± 0.11 | 0.83 ± 0.13 | 0.72 ± 0.04 |
| **C18:2 n-6** | 15.34 ± 0.55 * | **2.39 ± 0.16** * | **21.4 ± 1.8** * | **2.55 ± 0.19** * | **2.65 ± 0.02** * |
| C18:3 n-6 | 0.08 ± 0.00 | 0.07 ± 0.02 | 0.02 ± 0.04 | 0.08 ± 0.01 | 0.05 ± 0.03 |
| C18:3 n-3 (ALA) | 0.70 ± 0.14 | 0.65 ± 0.03 | 0.58 ± 0.18 | 0.78 ± 0.03 | 0.59 ± 0.07 |
| C18:4 n-3 | 1.14 ± 0.10 | 1.03 ± 0.09 | 0.99 ± 0.07 | 1.14 ± 0.11 | 0.92 ± 0.11 |
| C20:2 n-6 | 0.36 ± 0.05 | 0.26 ± 0.02 | 0.23 ± 0.01 | 0.33 ± 0.05 | 0.26 ± 0.05 |
| C20:4 n-6 | 1.15 ± 0.08 | 1.13 ± 0.07 | 1.24 ± 0.02 | 1.44 ± 0.07 | 1.08 ± 0.12 |
| **C20:5 n-3 (EPA)** | 5.43 ± 0.20 * | 4.88 ± 0.17 | **4.52 ± 0.06** * | 4.77 ± 0.14 | **3.99 ± 0.45** * |
| C22:5 n-3 | 1.37 ± 0.07 | 1.41 ± 0.19 | 1.14 ± 0.01 | 1.37 ± 0.02 | 1.15 ± 0.03 |
| C22:6 n-3 (DHA) | 11.68 ± 0.52 | 11.48 ± 0.61 | 10.93 ± 0.56 | 12.35 ± 0.13 | 10.66 ± 0.29 |
| **SFA** | 31.59 ± 0.23 * | 30.39 ± 0.29 | **26.9 ± 2.2** * | 30.61 ± 0.17 | 28.07 ± 0.27 |
| **MUFA** | 31.21 ± 0.13 * | **46.28 ± 0.50** * | 32.11 ± 0.12 | **44.54 ± 0.19** * | **50.57 ± 0.54** * |
| **PUFA** | 37.20 ± 0.36 * | **23.32 ± 0.74** * | 41.0 ± 2.1 | **24.85 ± 0.17*** | **21.35 ± 0.53** * |
| n3 | 20.33 ± 0.24 | 19.44 ± 0.86 | 18.16 ± 0.37 | 20.42 ± 0.18 | 17.31 ± 0.57 |
| n6 | 16.88 ± 0.51 | 3.88 ± 0.14 | 22.87 ± 1.76 | 4.43 ± 0.16 | 4.06 ± 0.06 |
| **n3/n6** | 1.21 ± 0.05 | **5.02 ± 0.38** * | **0.80 ± 0.04** * | **4.61 ± 0.19** * | **4.27 ± 0.19** * |
| **h/H** | 2.67 ± 0.05 * | 2.89 ± 0.05 | **3.55 ± 0.46** * | 2.86 ± 0.04 | **3.34 ± 0.05** * |
| **AI** | 0.52 ± 0.01 * | 0.48 ± 0.01 | **0.40 ± 0.04** * | 0.49 ± 0.01 | **0.41 ± 0.01** * |
| TI | 0.33 ± 0.00 | 0.31 ± 0.01 | 0.30 ± 0.03 | 0.29 ± 0.00 | 0.31 ± 0.01 |

Regarding PUFA, a considerable decrease in linoleic acid content in all coated fillets (from 2.39 ± 0.16 in Alg to 2.65 ± 0.02 in Car Pc) in comparison to the control (15.34 ± 0.55%) was observed, except for Alg Pc samples (21.4 ± 1.8%). Car Pc stands out for the lowest levels of DHA (10.66 ± 0.29) and EPA (4.52 ± 0.06) compared to the control, with values of 11.68 ± 0.52 and 5.43 ± 0.20 for DHA and EPA, respectively.

Among the FAs present in the sunflower oil, linoleic (C18:2) acid is the most susceptible to degradation, promoted by either oxidative or thermal reactions. At frying temperature, highly reactive peroxyl and alkyl radicals are formed, leading to chain reactions that result in PUFA degradation and formation of secondary oxidation compounds, namely volatile and polar compounds [11].

The results obtained suggest that both alginate- and carrageenan-based coatings promoted higher degradation of C18:2 since considerably lower values of this FA were found in Alg, Car, and Car Pc, in comparison with the control. Nevertheless, *P. canaliculata* extract seemed to have a protective effect on preventing C18:2 degradation in the alginate matrix, since 10 times higher values were observed in Alg Pc (21.4 ± 1.8%) compared to Alg (2.39 ± 0.16%). Considering that the FA profile was expressed as a percentage of total FA, a remarkable decrease in C18:2 may have influenced the remaining values. This can explain the results attained for oleic (C18:1), the most abundant FA in all the samples. In fact, the highest amounts of this MUFA, ranging from 37.49 ± 0.36% to 44.94 ± 0.95%, were found in samples with lower C18:2 values (in Car, Alg, and Car Pc samples), while Alg Pc and Control had similar values (27.14 ± 0.66% and 24.56 ± 0.10%, respectively). This hypothesis requires an in-depth study of the microstructure of coatings, as well as analyses of fatty acid degradation products.

The fatty acid profile determines the nutritional quality of foods. Several health lipid indices are usually used to evaluate fat quality. It is well established that an n-3/n-6 ratio between 1:1 and 5:1 is recommended to help prevent several chronic diseases. Moreover, the ratio between hypocholesterolemic (C18:1 and PUFA) and hypercholesterolemic (C14:0 and C16:0) fatty acids, known as the h/H index, is used to assess the effect of the FA profile in cholesterol metabolism, being recommended as a nutritional evaluation tool. The atherogenic index (AI), which is used to assess the risk for cardiovascular diseases, relates the proportion between the proatherogenic SFA and the main classes of antiatherogenic unsaturated fatty acids (UFA). The thrombogenic index (TI) is related to the tendency for clot formation in the blood vessels, corresponding to the relationship between the prothrombogenic (SFA) and antithrombogenic fatty acids (MUFA, n-6 and n-3 PUFA). Values lower than 1.0 and 0.5 for AI and TI, respectively, are desirable for a health-promoting diet [34].

In this study, higher values of the n3/n6 ratio (4.27 ± 0.19 in Car Pc to 5.02 ± 0.19 in Alg) were observed for samples with the lowest content of C18:2, conversely to those of the control (1.21 ± 0.05) and Alg Pc (0.80 ± 0.04). The coated fillets supplemented with *P. canaliculata* exhibited better health lipid indices. In fact, significantly higher values of h/H were attained for Alg Pc (3.55 ± 0.46) and Car Pc (3.34 ± 0.05) in comparison with the control (2.67 ± 0.05). Moreover, the best values of AI index were attained for Alg Pc (0.40 ± 0.04) and Car Pc (0.41 ± 0.01) in contrast to the control sample (0.52 ± 0.01). No statistically significant differences were observed for the TI index, with values around 0.3 for all the samples.

#### 3.3.4. Principal Component Analysis of Atlantic Mackerel Fillet Samples

Aiming to exhibit an overall and comparative perspective on the nutritional composition and fatty acid profile of pre-coated fried fish fillets, a principal component analysis (PCA) was carried out (Figure 6).

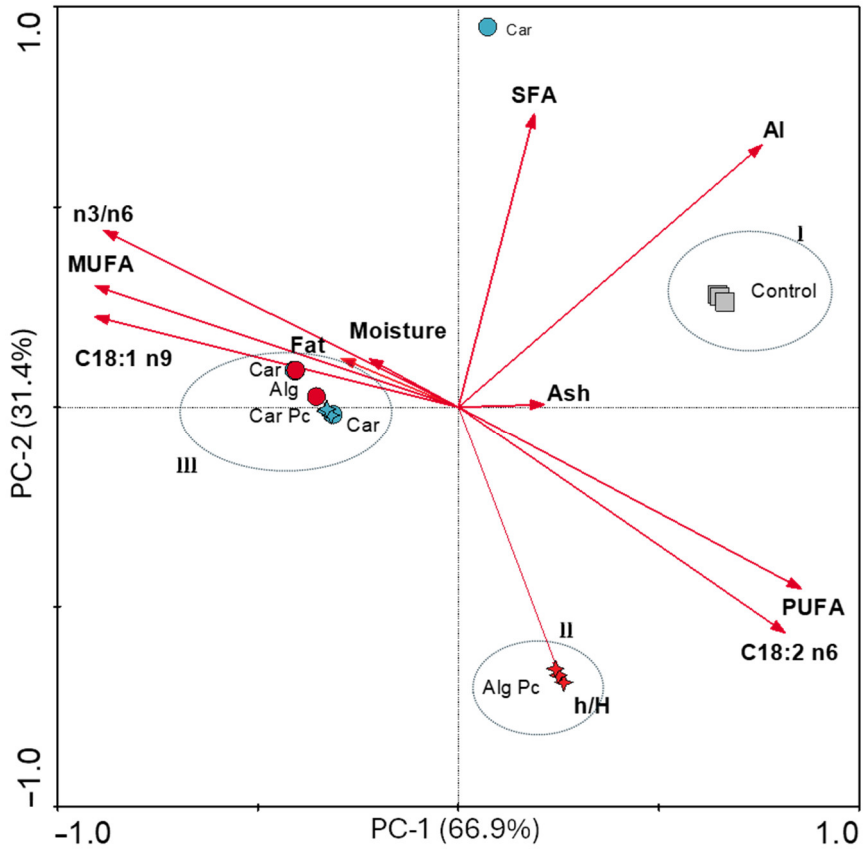


**Figure 6.** Principal component analysis (PCA) of pre-coated fried mackerel fillets concerning: (i) total saturated fatty acids (SFA); (ii) monounsaturated fatty acids (MUFA); (iii) polyunsaturated fatty acids (PUFA); (iv) oleic acid (C18:1); (v) linoleic acid (C18:2); (vi) n-3/n-6 ratio; (vii) Hypocholesterolemic/hypercholesterolemic (h/H); (viii) atherogenic (AI); (xi) thrombogenic (TI) indices; (x) moisture; (xi) fat and (xii) ash. Control: uncoated fried fillets; Alg: fillets coated with alginate solution; Alg Pc: fillets coated with alginate solution supplemented with *P. canaliculata*; Car: fillets coated with carrageenan solution; Alg Pc: fillets coated with carrageenan solution supplemented with *P. canaliculata*. PC-1 and PC-2 explain, respectively, 66.9% and 31.4% of data variability.

The first principal component (PC-1), accounting for 66.9% of the variability among samples, is positively correlated with PUFA, C18:2, and AI and negatively correlated with C18:1, MUFA, and n3/n6 ratio. The second principal component (PC-2), explaining 31.4% of the variability, is positively correlated with SFA and AI, while it is negatively correlated with h/H, C18:2 and PUFA. Conversely, TI, fat, moisture, and ash are the parameters that contribute the least to the variability among samples. As shown in Figure 6, the fried fillet samples are divided into three distinct groups: (i) group I, which corresponds to the control samples, shows the highest values of SFA and AI, and the lowest levels of C18:1, and MUFA (ii) group II, corresponding to the Alg Pc samples, is characterized by the highest values of h/H, C18:2, and PUFA, and (iii) group III, comprising the Car Pc, Alg and Car samples, which are more similar to each other. This group is distinguished by the highest levels of C18:1, MUFA, and the n3/n6 ratio, along with the lowest values of C18:2. It is worth mentioning that coated fillets stand out as a healthier food product, with improved nutritional characteristics. In fact, the application of coatings in fish samples (Groups II and III) promoted a decrease in SFA and an increase in MUFA, thus leading to better AI and h/H health lipid indices. The effect of *P. canaliculata* extract was more evident in alginate-based coating, particularly in C18:1 and C18:2 contents and, consequently, in the n3/n6 ratio.

## 4. Conclusions

This study aimed to explore the potential of seaweeds, as an outstanding source of bioactive compounds, to overcome some of the limitations related to frying foods, particularly their high fat content and susceptibility to oxidation. For this purpose, alginate and carrageenan coatings were supplemented with ethanolic extracts of *P. canaliculata* and applied to pre-fried mackerel fillets.

Among the evaluated parameters, the fatty acid profile of the fish fillets was the most influenced by the applied coatings, which consequently affected the health lipid indices. The seaweed extracts significantly improved the health-related lipid parameters (h/H, AI, and n3/n6 ratio) and promoted a slight reduction in fat while increasing water content. No significant differences were obtained in colour and textural attributes. Therefore, a functional food with health-promoting benefits was obtained. In the near future, further studies are recommended, particularly concerning the microstructure of the polysaccharide coatings.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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