Discover Food

RESEARCH Open Access

Physical, morphological and techno-functional properties of extruded corn snacks fortified with brown seaweed

Vojislav Banjac[1], Jovana Kojić[2], Bojana Filipčev[1], Nikola Maravić[1], Viktor Stojkov[1], Strahinja Vidosavljević[1], Brijesh Tiwari[3] and Milica Pojić[1*]

*Correspondence:
Milica Pojić
milica.pojic@fins.uns.ac.rs
[1]Institute of Food Technology, University of Novi Sad, Bulevar cara Lazara 1, Novi Sad 21000, Serbia
[2]BioSense Institute, University of Novi Sad, Dr Zorana Đinđića 1, Novi Sad 21000, Serbia
[3]Department of Food Chemistry and Technology, Teagasc Ashtown Food Research Centre, Ashtown, 15, Dublin, Ireland

Abstract
Extrusion is common in snack production, but many products are nutritionally limited. Brown seaweeds are sustainable fortifying ingredients rich protein, fibre, and minerals. This study aimed to assess the effects of brown seaweed fortification in corn-based snack on the quality-related properties of extruded products. Corn-based extrudates were enriched with *Saccharina latissima* (5%) and *Alaria esculenta* (5–15%) and analysed for physical, textural, morphological, and techno-functional properties, along with compositional characterization. Seaweed fortification increased dietary fibre (insoluble dietary fibre 1.42–4.86 g/100 g; soluble dietary fibre 0.49–2.03 g/100 g), and mineral content, but reduced expansion (4.37–2.97) and porosity (88.12–69.15%), resulting in denser (bulk density 53.52–77.38 kg/m^3), harder (33.22–60.95 N) and less crispy products (7.43–5.43 N). Techno-functional properties remained stable across formulation (water solubility index 26.44–31.36%; water absorption index 5.59–6.66 g/g; oil absorption capacity 2.06–2.14 g/g). These findings highlight brown seaweeds as promising sustainable ingredients for extruded snacks, where moderate inclusion levels can combine compositional enhancement with acceptable texture.

Keywords *Alaria esculenta*, Extrusion, Fortified snack, *Saccharina latissima*, Sustainability

1 Introduction

Extrusion technology is a highly versatile and efficient processing method widely used in the production of snacks, ready-to-eat (RTE) breakfast cereals, texturized vegetable proteins, meat analogues, and pasta. The process combines several technological operations including mixing, cooking, and forming enabling modulation of structural and sensory properties of food products by adjusting processing parameters (temperature, feed moisture, screw configuration, and die design) [1]. Apart from technological versatility, extrusion also offers opportunities to enhance nutritional quality, for example

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

by improving protein and starch digestibility, increasing the bioaccessibility of certain micronutrients, and reducing anti-nutritional factors [2–4].

Despite these advantages, conventional cereal-based extruded snacks are typically made with refined cereal flours and starches. Consequently, they are high in rapidly digestible carbohydrates, but low in protein, dietary fiber, and essential micronutrients. Such formulations contribute to postprandial glucose spikes, hyperinsulinemia, and long-term health risks, including insulin resistance, type 2 diabetes, and cardiovascular disease [5]. In addition, these carbohydrate-rich products often lack satiety, thereby promoting overeating and weight gain [6]. As consumer awareness of nutrition and sustainability grows, reformulation of extruded foods with nutrient-dense and low-glycemic ingredients is becoming a research and industry priority. In this context, algae (micro and macro) have gained increasing attention as novel food ingredients due to their rich profile of proteins, essential amino acids, complex polysaccharides, polyunsaturated fatty acids, pigments, vitamins, minerals, and polyphenols [7]. Although microalgae (e.g. Spirulina and Chlorella) and microalgal derived compounds have been widely investigated as fortifying ingredients in extruded and baked products demonstrating improvements in protein content and micronutrient levels [8–10], their incorporation may affect product expansion due to protein–starch competition for water during extrusion. In addition, the characteristic green colour and fish-like flavour of certain microalgae species have been reported to negatively influence consumer acceptance at higher inclusion levels [11, 12]. However, the fortification of extruded snack formulations with macroalgae (seaweeds) remains limited, and brown macroalgae are particularly underexplored in extrusion systems compared with red and green species. Cian et al. [13] demonstrated the utilization of red seaweeds for enrichment of extruded corn-based snacks. Snack enriched with seaweed *Porphyra columbina* (3.5 g/100 g) exhibited higher level of bioactive compounds compared to control maize extrudates with increased bioaccessibility of minerals and bioactive compounds, including ACE inhibitory peptides, phenolics, and antioxidants. Singh et al. [14] fortified extruded snack based on corn and rice flour (70:30) with green seaweed *Ulva lactuca.* They reported that increasing seaweed concentration reduced expansion and porosity while increasing bulk density, and identified optimal processing conditions (approximately 6–8% Ulva, 135–140 °C, 11–12% feed moisture) to achieve improved product characteristics.

Brown seaweeds such as *Alaria esculenta* and *Saccharina latissima* are abundant, underutilized marine resources, rich in polysaccharides, fibers, minerals, iodine, vitamins, and bioactive compounds, and cultivated with minimal environmental impact since they require no land, freshwater, fertilizers, or pesticides [15]. Their incorporation into cereal-based extrudates thus represents an opportunity not only to improve nutritional value but also to advance sustainability goals. In particular, although the general impact of fiber-rich ingredients on extrusion behavior is well documented, more specific insight into how the compositional characteristics of brown seaweeds, especially their insoluble fiber matrix and multivalent mineral content interact with starch during extrusion remains less explored. Moreover, studies that simultaneously link compositional shifts with structural, physical and techno-functional properties in brown seaweed-fortified extrudates are relatively limited. In addition, direct comparative evaluation of different brown seaweed species in starch-based, extrusion-expanded snack systems has so far received little attention.

Therefore, the aim of this study was to systematically evaluate the impact of brown seaweed incorporation (*Alaria esculenta*, *Saccharina latissima*) on the physical, structural, textural and techno-functional properties of extruded corn snacks, while relating these changes to compositional characteristics.

2 Materials and methods

2.1 Materials

Dry biomass of *Alaria esculenta* and *Saccharina latissima* was supplied by Teagasc (Ireland), where post-harvest treatment was performed. Conventional water stirring (CS) was conducted at temperature ~ 15 °C for 10 min at 50 rpm using a biomass-to-water ratio of 1:4 (w/v). The biomass was oven-dried at 50 °C for 6.5 h. The raw biomass originated from cultivated material harvested at Bantry Marine Research Station (Ireland) during the spring 2023. The material was supplied as a single production batch for research purposes. Prior to processing, the dried algal material was milled to powder using a hammer mill equipped with 2 mm sieve (ABC Engineering, Serbia). Yellow corn grits used in this study (protein 6.5 g/100 g, fat 0.59%, ash 0.31%, starch 74.3%, dietary fibers 5.73%) was purchased from Mirotin Tisa (Savino selo, Serbia).

2.2 Snack production

Dry seaweed powder was incorporated into the corn grits at three inclusion levels (5, 10, and 15%, w/w for *Alaria esculenta* and 5%, w/w for *Saccharina latissima*). The selected inclusion levels were chosen to represent a realistic fortification range for cereal-based extruded snacks, balancing nutritional enhancement and technological feasibility. Preliminary trials indicated that inclusion levels above 15% significantly impaired expansion and product structure, while lower levels (< 5%) resulted in limited compositional impact. The inclusion level of *Saccharina latissima* was limited to 5% due to its naturally high iodine content, which may raise nutritional and regulatory concerns at higher incorporation levels, as residual iodine concentrations can remain substantial even after post-harvest treatments [16]. Five extrudate formulations were prepared: (F0) Control (corn-based snack without seaweed); (F1) 5% *Saccharina latissima*; (F2) 5% *Alaria esculenta*; (F3) 10% *Alaria esculenta*; and (F4) 15% *Alaria esculenta*. Each formulation was produced in a single independent extrusion run under controlled processing conditions. Mixing was performed in a twin-shaft paddle mixer of a laboratory vacuum coater (model F-6-RVC, Forberg International AS, Norway) for 90 s, with a batch size of 4 kg. Extrusion was carried out using a co-rotating twin-screw extruder (Bühler BTSK-30, Bühler, Uzwil, Switzerland) with a total barrel length of 880 mm (L/D = 28:1) and seven barrel sections. The extruder was equipped with a jacketed heating/cooling system. Barrel Sects. 2–4 were maintained at 80 °C, while Sects. 6–7 were set at 115 °C. A die plate with a single 4-mm opening and cone inlet geometry (total die area 12.56 mm^2) was used, with a screw configuration optimized for directly expanded products [17]. The feed rate (45 kg/h) and screw speed (800 rpm) were kept constant. The target moisture content in the barrel (~ 16%) was achieved by adding water directly into the second barrel section via a water pump. The required amount of water was calculated from the initial material moisture (measured by a rapid moisture analyzer) and the material throughput. Die pressure, die temperature, motor load, and specific mechanical energy were recorded directly from the extruder's PLC system. Product length was adjusted using a

die-face cutter fitted with six knives operating at 500 rpm. After extrusion, samples were cooled at ambient conditions and packed in paper bags prior to further analyses. The processing parameters are presented in Table 1.

2.3 Chemical composition of snacks

The chemical composition of the samples was determined according to the Approved Methods of Analysis of the AACC (2000), including moisture (44-15.02), ash (08-01.01), protein (46-13.03), fat (30-25.01), and dietary fiber (32-05.01). Total carbohydrates were determined by difference. Values are expressed as % (w/w) on a fresh weight basis (as is). All measurements were performed in triplicate.

For mineral analysis, 1 g of powdered snack sample was digested with 7 mL of nitric acid and 1 mL of hydrogen peroxide using a microwave digestion system. After digestion, the solutions were diluted to 25 mL with deionized water. Fe, Cu, K, Na, Mg and Ca were determined by flame atomic absorption spectrometry (Thermo Scientific, iCE 3000 Series, USA) using an air–acetylene flame at the following analytical wavelengths: Fe (248.3 nm), Cu (324.8 nm), Mn (279.5 nm), Zn (213.8 nm); Na (589.6 nm), K (766.5 nm), Mg (285.2 nm) and Ca (422.6 nm). Operating conditions were set in accordance with EN ISO 6869:2008. All analyses were performed in triplicate.

2.4 Physical properties

2.4.1 Expansion index (EI)

EI was determined as the ratio of the extrudate diameter (Re) and the die diameter (Rm) according to Eq. (1):

$$EI = \frac{Re}{Rm} \tag{1}$$

Table 1 Extrusion processing parameters for production of snack product

	F0	F1	F2	F3	F4
Temperature[a] (°C)					
Section 3	76.1	76.1	76.0	76.0	76.0
Section 6	106.1	102.3	104.3	98.9	99.3
Die	147.0	166.0	161.0	165.0	173.0
Screw speed (RPM)	800	800	800	800	800
Die diameter (mm)	4	4	4	4	4
Open die area (mm^2)	12.56	12.56	12.56	12.56	12.56
Throughput (kg/h)	45	45	45	45	45
Water throughput (kg/h)	3.6	3.6	3.6	3.5	3.5
Moisture content[b] (%)	16.20	16.20	16.22	16.08	16.11
Die pressure (bar)	17.6	16.4	14.8	11.0	6.6
Torque[c] (Nm)	154.0	145.2	145.2	138.6	134.2
SME[d] (Wh/kg)	195.3	189.8	191.2	181.5	176.4
Knife speed (RPM)	500	500	500	500	500

[a]Measured by sensors located in the extruder barrel

[b]Total moisture content during extrusion calculated based on moisture content of the material after conditioning, material throughput and water throughput in the extruder barrel

[c]Motor load, 100% torque is 220 Nm

[d]Specific mechanical energy

The diameters of the extrudates were measured using a movable, beak gauge (MIB Messzeuge GmbH, Spangenberg, Germany) according to [18]. The expansion characteristics of the snack product were determined in 10 replicates.

2.4.2 Bulk density

Bulk density was determined according to previously described procedures for extruded snack products [19] using a bulk density tester (Tonindustrie-Geräte GmbH, Goslar, Germany). The mass of the material filling a container of known volume (1 L) was recorded and expressed as g/L. Measurements were performed in four replicates.

2.4.3 Colour measurement

The colour of powdered snack products was measured using a Chroma Meter CR-400 (Konica Minolta Co., Ltd., Osaka, Japan) equipped with a CR-A50 extension, suitable for this type of sample, in the CIE Lab colour space according to [18]. Prior to measurement, the samples were ground with a KN 295 Knifetec laboratory mill (Foss, Denmark). Measurements were performed in ten replicates.

Colour difference (ΔE) and browning index (BI) was calculated using the Eqs. (2), (3) and (4) according to [20, 21]:

$$\Delta E = \sqrt{(L_0 - L^*)^2 + (a_0 - a^*)^2 + (b_0 - b^*)^2} \tag{2}$$

$$BI = \frac{100\,(X - 0.31)}{0.17} \tag{3}$$

$$X = \frac{a^* + 1.75L^*}{5.645L^*} + a^* - 0.3012b^* \tag{4}$$

where L_0, a_0, b_0 are the colour values of the control sample.

2.4.4 Porosity

Extrudate samples were cut transversely into thin slices using a sharp blade in order to expose the internal structure. Images of the cross-sections were captured using a Canon digital camera with 5 × magnifications under uniform lighting conditions. The images were processed using open-source Python software according to [22]. First, they were converted to grayscale, and subsequently binarized into black-and-white format. In this process, pixels with RGB values equal to 255 were converted to white, while pixels with values below 128 were converted to black.

In the binarized images, black areas represented pores, whereas white areas represented the solid matrix of the snack. Porosity (P, %) was calculated using the PoreSpy image analysis package for Python, as the ratio of black pixels (pores) to total pixels (pores + solid matrix), calculated according to Eq. (5) and expressed as a percentage:

$$P = \frac{A_{pores}}{A_{total}} \times 100 \tag{5}$$

2.4.5 Textural properties

Snack hardness was measured by diametric compression using a TA-XT2 Texture Analyzer (Stable Micro Systems, Surrey, UK), following the procedure described by Bokić

et al. [23]. From each sample, 15 extrudates were tested. Three extrudates were placed horizontally on the flat platform and compressed with a cylindrical stainless-steel probe (45 mm diameter), equipped with a 50-kg load cell and a 100-g trigger force. Instrument parameters were: pre-test speed 2.0 mm/s, test speed 1.0 mm/s, post-test speed 10.0 mm/s, and probe distance 7 mm. Hardness was defined as the maximum force recorded at the first fracture point on the force-distant curve and expressed in Newtons (N). Crispiness was evaluated using three parameters: crispiness work (Cw), crispiness index (Ci) and the number of fracture peaks. Texture Exponent software v.5.1.2.0 (Stable Micro Systems, UK) was used to obtain values from the force-deformation curve [23]. Crispiness work (Cw) was calculated by Eq. (6) as the ratio between the area under the force-distance curve (A, N·mm) and the number of peaks (N), according to [24]:

$$C_w = \frac{A}{N} \tag{6}$$

Crispiness index (C_i) was determined as the ratio of normalized curve length (L_N, mm/N) to the product of the curve area (A, N·mm) and the mean force (F_{mean}, N), where F_{mean} represents the sum of all forces divided by the number of peaks according to Eq. (7) [24]:

$$C_i = \frac{L_N}{A\ x\ F_{mean}} \tag{7}$$

The number of peaks corresponds to the number of structural fractures in the sample during compression [25]. Higher crispiness is indicated by increased number of fractures and higher crispiness index but lower crispiness work [26].

2.4.6 Morphological properties

Morphological examination was performed on Apreo 2 C Scanning Electron Microscope (SEM, Thermo Fisher Scientific, Waltham, MA, USA). Samples were fixed on aluminum stubs using carbon adhesive tape. Images were made using secondary electrons and backscattered (SE/BSE) (2 kV, 0.10nA) at a working distance of 5 mm under high vacuum conditions [27].

2.5 Techno-functional properties

2.5.1 Water absorption index and water solubility index

Water absorption index (WAI) and water solubility index (WSI) were determined according to the procedure described by [28]. Prior to analysis, samples were ground using a laboratory hammer mill (Retsch SK1, Retsch GmbH, Haan, Germany). Ground material (0.20 ± 0.001 g) was mixed with 5 mL of distilled water in a 15 mL centrifuge tube, vortexed for 2 min, and centrifuged at 6300 rpm for 20 min. The supernatant was decanted into an evaporating vessel, while the precipitate was weighed. WAI (g/g) was calculated according to formula (8):

$$WAI = \frac{m_p}{m_s} \tag{8}$$

where m_p is the weight of the precipitate and m_s is the weight of sample (g).

WSI (g/100 g) was determined as the mass of dissolved solids in the supernatant after evaporation, expressed relative to the initial dry sample mass (Formula (9)):

$$WSI = \frac{m_{ds}}{m_s} \tag{9}$$

where m_{ds} is the weight of dry solids from the supernatant and m_s is the weight of sample (g).

2.5.2 Oil absorption capacity

Oil absorption capacity (OAC) was determined by a centrifugation method adapted from Kalahal et al., where a known mass of sample was mixed with oil, allowed to interact, and centrifuged to remove unabsorbed oil. according to the centrifugation method described by [29]. Approximately 0.50 g of ground extruded sample was weighed into a 15 mL polypropylene test tube. Subsequently, 5.0 mL of rapeseed oil was added and the mixture was vortexed for 15 s. Then, an additional 5.0 mL of the same oil was introduced and the sample was vortexed again for 10 s. The oil-sample dispersion was allowed to stand at ambient temperature for 30 min, and then centrifuged at 3 000 rpm for 30 min. After centrifugation, the supernatant oil was decanted and the tube was inverted to allow residual oil drainage. The oil absorption capacity (OAC) was calculated by subtracting the weight of the sample after centrifugation from its initial weight, and dividing by the initial weight of the sample; results were expressed as grams of absorbed oil per gram of sample (g oil/g sample). All measurements were carried out in triplicate.

2.6 Statistical analysis

The results are presented as mean values ± standard deviation of individual measurements. Statistical differences among formulations were assessed by one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test, using Statistica 10.0 software (StatSoft Inc., Tulsa, OK, USA). Differences were considered statistically significant at $p < 0.05$. Pearson's correlation coefficients were calculated to examine relationships between compositional and physical/functional parameters.

3 Results and discussion

3.1 Nutritional value of extruded snacks

The incorporation of brown seaweeds (*Saccharina latissima* and *Alaria esculenta*) into cereal-based snacks clearly modified their proximate composition (Table 2). Moisture content ranged from 6.78 to 7.33 g/100 g. The lowest value was observed in snack formulation F1 (6.78 g/100 g), while formulations F2 and F3 showed slightly higher moisture levels (7.33 and 7.22 g/100 g, respectively) compared to the control (7.07 g/100 g). The moisture variations can be linked to the water-binding properties of alginate and fucoidan present in brown algae, compounds known to influence water retention during extrusion [30]. Protein content increased from 7.39 g/100 g in the F0 to 8.68 g/100 g in the formulation F1. A moderate increase was also observed in snack formulation F2 (8.02 g/100 g). However, further increases in *Alaria esculenta* level (F3-F4) did not result in additional protein enrichment, with values remaining relatively stable at 7.73–7.74 g/100 g, suggesting that at higher substitution levels, the change in composition was characterized more by increasing mineral and fiber fractions than by proportional increase in

Table 2 Proximate and mineral composition of different formulations of extruded snack

	F0	F1	F2	F3	F4
Water, g/100 g	7.07 ± 0.03^{a}	6.78 ± 0.06^{b}	7.33 ± 0.06^{c}	7.22 ± 0.03^{c}	7.15 ± 0.06^{a}
Protein, g/100 g	7.39 ± 0.01^{a}	8.68 ± 0.05^{b}	8.02 ± 0.05^{c}	7.73 ± 0.07^{d}	7.74 ± 0.05^{d}
Ash, g/100 g	0.07 ± 0.0^{a}	1.77 ± 0.01^{b}	1.35 ± 0.0^{c}	2.21 ± 0.01^{d}	4.21 ± 0.01^{e}
Carbohydrates	85.46 ± 0.04^{a}	82.76 ± 0.0^{b}	83.29 ± 0.01^{c}	82.83 ± 0.1^{b}	80.88 ± 0.09^{d}
Insoluble DF, g/100 g	1.42 ± 0.07^{a}	2.49 ± 0.09^{b}	2.74 ± 0.06^{c}	3.74 ± 0.05^{d}	4.86 ± 0.11^{e}
Soluble DF, g/100 g	0.49 ± 0.03^{a}	1.33 ± 0.03^{b}	1.43 ± 0.02^{c}	1.53 ± 0.01^{d}	2.03 ± 0.02^{e}
Total DF, g/100 g	1.91 ± 0.04^{a}	3.82 ± 0.06^{b}	4.16 ± 0.07^{c}	5.27 ± 0.06^{d}	6.89 ± 0.09^{e}
Zn, mg/kg	3.9 ± 0.04^{a}	17.1 ± 0.03^{b}	11.44 ± 0.28^{c}	6.6 ± 0.19^{d}	6.42 ± 0.28^{d}
Cu, mg/kg	1.48 ± 0.02^{a}	4.27 ± 0.04^{b}	2.62 ± 0.01^{c}	2.36 ± 0.0^{d}	1.84 ± 0.04^{e}
Fe, mg/kg	9.04 ± 0.01^{a}	15.52 ± 5.61^{a}	14.06 ± 4.35^{a}	26.19 ± 14.85^{a}	28.7 ± 17.05^{a}
Mg, mg/kg	171.54 ± 0.55^{a}	497.17 ± 3.2^{b}	471.38 ± 4.12^{c}	812.49 ± 0.07^{d}	1125.62 ± 9.27^{e}
K, mg/kg	841.1 ± 6.41^{a}	3354.36 ± 14.45^{b}	2540.92 ± 7.03^{c}	5648.56 ± 5.17^{d}	7923.65 ± 35.32^{e}
Na, mg/kg	192.0 ± 1.69^{a}	2432.24 ± 20.51^{b}	1817.5 ± 7.37^{c}	4027.06 ± 2.93^{d}	5826.52 ± 0.23^{e}
Ca, mg/kg	56.34 ± 1.57^{a}	687.6 ± 2.5^{b}	1154.85 ± 3.77^{c}	1270.48 ± 5.41^{d}	2125.85 ± 10.3^{e}
Mn, mg/kg	0.89 ± 0.02^{a}	1.24 ± 0.01^{b}	1.26 ± 0.0^{b}	1.88 ± 0.01^{c}	2.18 ± 0.02^{d}

Results are expressed as mean ± standard deviation. Values within the same row followed by different superscript letters are significantly different ($p < 0.05$)

protein content. The protein and polysaccharide composition of *Saccharina latissima* and *Alaria esculenta* is strongly affected by seasonal factors and processing methods, which may also contribute to the observed differences in water and protein content [30–32]. Ash content significantly increased with seaweed incorporation, rising from 0.07 g/100 g in the F0 to 1.77 g/100 g in snack F1. In the *Alaria esculenta* formulations, ash significantly increased from 1.35 g/100 g (F2) to 2.21 g/100 g (F3) and reached 4.21 g/100 g in F4. This trend reflects the well-documented mineral richness of brown seaweed and is consistent with the reported ask content in *Saccharina latissima* (~ 39 g/100 g dry weight) compared with *Alaria esculenta* (~ 26 g/100 g dry weight). In contrast, the calculated carbohydrate fraction decreased as ash and dietary fiber increased. These changes are consistent with the known composition of brown algae and align with previously published studies that examined the fortification of extruded snacks with seaweed or other bioresources. A comparable trend was reported by Amer & Rizk [33], where ash increased from 0.49% to 1.29% by fortification, accompanied by a reduction in carbohydrate content (from 53.60% in the control to lower values in fortified samples). Although the absolute values differ due to the higher mineral content of seaweeds compared to spices, the directional effect remains consistent [33]. The incorporation of seaweed into corn-based extrudates significantly affected the dietary fiber profile, particularly the distribution between insoluble (IDF) and soluble dietary fiber (SDF). Insoluble fiber significantly increased from 1.42 g/100 g in the F0 to 4.86 g/100 g in F4, while soluble fiber increased from 0.49 g/100 g to 2.03 g/100 g across the formulations. These findings confirm that brown seaweeds are valuable sources of both fiber fractions, with *Saccharina latissima* and *Alaria esculenta* providing considerable levels of soluble polysaccharides such as alginates and laminarins. Beyond the compositional contribution of seaweed itself, the extrusion process also contributes to the increase in SDF. High temperature and shear promote partial depolymerization of insoluble fiber fractions and transformation of IDF into more soluble components. Sinaki & Koksel demonstrated that extrusion significantly decreased IDF while increasing SDF in pulse-based extrudates, confirming the structural modification of dietary fiber during processing. In the present study, the

increase in soluble fiber from 0.49 to 2.03 g/100 g likely reflects a combined effect of the intrinsic seaweed composition and extrusion-induced fiber transformation [34].

Fortification of corn-based snacks with *Alaria esculenta* and *Saccharina latissima* resulted in significant changes in mineral composition compared to the control. In *Alaria* formulations, potassium increased from 841 mg/kg in the F0 to 7924 mg/kg in F4. Iron rose from 9.04 mg/kg in the F0 to 28.70 mg/kg in F4, respectively. Magnesium increased from 171.54 mg/kg (F0) to 1125.62 mg/kg (F4), while calcium showed a substantial rise from 56.34 mg/kg in the F0 to 2125.85 mg/kg in the F4. Zinc enrichment was most evident in F1, increasing from 3.9 mg/kg in the F0 to 17.1 mg/kg in the F1. Copper exhibited moderate increases in both seaweed-based snacks, whereas sodium significantly increased across all fortified formulations, reaching 5827 mg/kg in the F4 compared to 192 mg/kg in the F0. These results are in accordance with studies published so far. Macroalgae are recognized as rich sources of essential minerals, often containing much higher levels of potassium, magnesium, calcium, iron, and zinc than vegetables [35]. Previous studies on extruded snacks fortified with *Ulva lactuca* (6–8% inclusion) demonstrated successful incorporation of seaweed, resulting in increased ash (mineral) content which increased to approximately 2% in the fortified product [14]. In the present study, ash reached 4.21 g/100 g in F4, reflecting both the higher substitution level and the higher mineral density of brown seaweeds compared to green species [14]. These findings confirm that seaweed fortification can significantly enhance the mineral profile of cereal-based snacks. *Alaria esculenta* demonstrated stronger potential for enriching potassium, magnesium, calcium, and iron, whereas *Saccharina latissima* was particularly effective for zinc and copper. At the same time, the observed rise in sodium reflects the naturally high sodium content of brown seaweeds [35] and should be considered carefully in product formulation or use in other product categories, such as seasoning blends, flavoring ingredients or functional toppings, where mineral contribution may be technologically or nutritionally justified. Recent studies have confirmed that extrusion enhances the bioaccessibility of iron and magnesium by inactivating antinutrients [36, 37]. Seaweeds including *Alaria esculenta* and *Saccharina latissima* contain compounds that may act as antinutritional factors, such as phenolic compounds - phlorotannins, which can chelate minerals, as well as soluble polysaccharides (alginates, fucoidans, laminarins) that may reduce the absorption of calcium and iron [38, 39].

3.2 Physical properties of extruded snacks

Physical properties of extruded snacks include bulk density, diameter, expansion index (EI), porosity, color and morphological properties. Density and EI provide insight into the degree of expansion and modifications in the cellular structure of the product, while porosity reflects the openness of the internal structure, which is closely linked to crispness and consumer perception. Color is another important physical attribute, as it influences product appearance and acceptability [40, 41]. The appearance of the control and seaweed-enriched snacks is shown in Fig. 1.

The physical properties of the snacks are summarized in Table 3.

Statistically significant differences ($p < 0.05$) were observed for bulk density, diameter, and expansion index between the samples. The F0 (corn-based snack) sample exhibited the lowest bulk density (53.52 kg/m^3) and the highest expansion index (4.37), being consistent with maximal expansion. Formulations F1 and F2 showed slightly to moderately

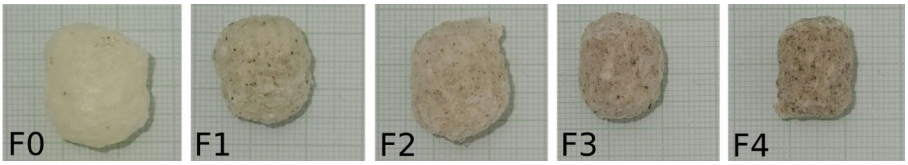


Fig. 1 Appearance of different snack formulations produced with different inclusion levels of seaweed

Table 3 Physical properties of different snack formulations

Formulation	Bulk density (kg/m^3)	Diameter (mm)	Expansion index	Porosity
F0	53.52 ± 0.46^{a}	17.5 ± 0.39^{a}	4.37 ± 0.1^{a}	88.12 ± 1.08^{a}
F1	58.32 ± 0.1^{b}	15.12 ± 0.22^{b}	3.78 ± 0.05^{b}	80.73 ± 1.01^{b}
F2	54.9 ± 0.35^{c}	15.63 ± 0.54^{b}	3.91 ± 0.14^{b}	79.62 ± 0.74^{b}
F3	62.3 ± 0.26^{d}	14.12 ± 0.53^{c}	3.53 ± 0.13^{c}	72.23 ± 1.2^{c}
F4	77.38 ± 0.17^{e}	11.88 ± 0.43^{d}	2.97 ± 0.11^{d}	69.15 ± 0.85^{d}

Results are expressed as mean ± standard deviation. Values within the same column followed by different superscript letters are significantly different ($p < 0.05$)

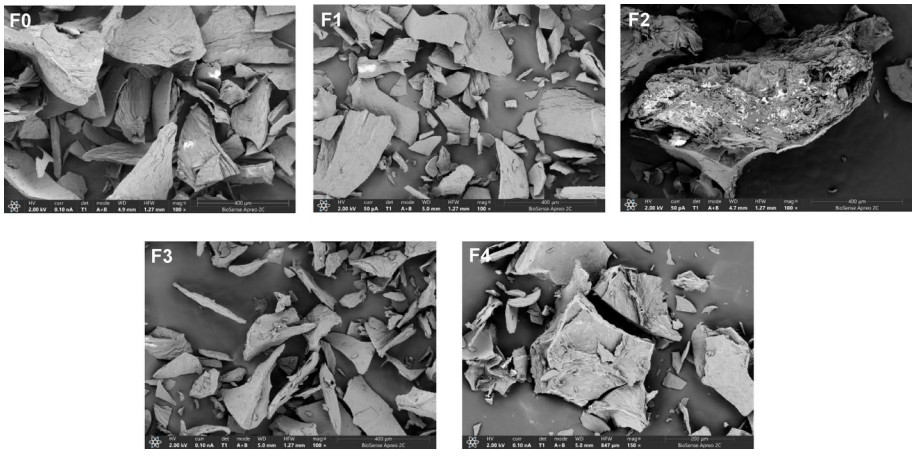


Fig. 2 Scanning electron micrographs of different formulations of extruded snacks

higher bulk density values (58.32 and 54.90 kg/m^3, respectively), accompanied by a reduction in expansion index (3.78–3.91). Formulations F3 and F4 exhibited significantly higher bulk density (62.3–77.4 kg/m^3) and lower expansion index values (3.53–2.97) compared to the control (F0), indicating a pronounced reduction in puffing and expansion efficiency with increasing seaweed incorporation. A similar trend has been reported for corn-based extrudates fortified with *Ulva lactuca*, where bulk density values ranged from 0.10 to 0.13 g/ml (i.e., 100–130 kg/m^3) and increased significantly with higher seaweed concentration [14]. In that study, increasing Ulva levels resulted in reduced expansion and higher product compactness, consistent with the structural dilution of starch and interference with bubble growth during extrusion. Although the absolute bulk density values in the present study (53.52–77.4 kg/m^3) were lower than those reported by Singh et al. (2016), the direction of change was comparable, confirming that macroalgal incorporation generally leads to denser extrudates [14]. This effect is often attributed to the incorporation of dietary fiber, which can act as a diluent, reducing starch concentration and limiting expansion. Soluble fiber, in particular, is less detrimental than insoluble fiber, but overall fiber addition tends to reduce expansion and elevate density [34]. To

better understand these changes in bulk density and expansion, the microstructural features observed by SEM (Fig. 2) were interpreted in relation to dietary fibre fractions and mineral composition (Table 2).

SEM image of the F0 revealed a starch–protein matrix with fractured walls and irregular surfaces which reflect the collapse and breakage of pore walls. The presence of cavities and ruptures indicates the porous cellular structure formed during expansion. SEM image of the F1 shows a slightly denser starch–protein matrix with thicker, more compacted walls compared to the control. The structure exhibited fewer and narrower cavities, suggesting that seaweed incorporation reduced expansion and contributed to partial collapse of the cellular network. In contrast to the F0, where more open cavities are evident, the formulation F1 is characterized with more rigid and less porous microstructure. SEM image of the F2 shows a starch–protein matrix with reduced porosity compared to the F0, in accordance with measured decrease from 88% to ~ 80% (Table 4). The pore network appears less open and cavities are narrower, indicating partial collapse of the cellular structure. In comparison with the F1, containing *Saccharina latissima* which exhibited thicker and more compacted walls due to the predominance of soluble fibers forming gel-like structures, the Alaria-enriched matrix exhibited a less consolidated and more heterogeneous arrangement, consistent with its higher proportion of insoluble fibers that act as rigid particles interfering with matrix uniformity (Table 2). At an equal inclusion level of brown seaweed, *Saccharina latissima*-enriched extrudate preserved a more open, control-like microstructure (F1) than *Alaria esculenta*-enriched extrudate (F2). This observation aligns with the composition data: the F2 had ~ 50% higher insoluble dietary fiber than the F1 (3.74 vs. 2.49 g/100 g), while soluble fiber rose only modestly (+ 7.5%). Higher insoluble fiber fractions are well known to act as fillers and disrupt bubble growth, reducing expansion and porosity in extruded matrices, whereas soluble fractions tend to be less disruptive [42]. Moreover, F2 had substantially higher Ca (+ ~ 68% vs. Saccharina) and generally higher content of multivalent minerals (e.g. Mg), which can stiffen the starch matrix and promote bubble collapse or thicker cell walls, further lowering porosity [43]. Taken together, the combination of significantly higher insoluble DF and higher mineral content in the F2 provided an explanation for its denser SEM morphology and the shift toward lower crispness and higher hardness. As the *Alaria esculenta* proportion increased in the formulations (F2-F4), the microstructure became denser, with reduced porosity, thicker walls and irregular pore distribution. Such reductions in expansion and porosity upon addition of fiber-rich or non-starch ingredients are consistent with literature on dietary-fiber enriched extrudates [42]. These structural changes contributed to decreased crispness and increased hardness of the extrudates, in line with the concept of bubble collapse and wall rupture under modified mechanical strength of the matrix [44].

Table 4 Colour parameters of different extruded snack formulations

Formulation	L*	a*	b*	ΔE	BI
F0	90.85 ± 0.2^{a}	-1.66 ± 0.1^{a}	29.18 ± 1.03^{a}	0.79 ± 0.63^{a}	1.85 ± 0.15^{a}
F1	83.95 ± 0.28^{b}	-0.36 ± 0.07^{b}	18.68 ± 0.39^{b}	12.64 ± 0.33^{b}	1.89 ± 0.04^{a}
F2	82.47 ± 0.28^{c}	0.41 ± 0.09^{c}	19.66 ± 0.36^{c}	12.85 ± 0.32^{b}	2.71 ± 0.07^{b}
F3	78.55 ± 0.8^{d}	0.7 ± 0.23^{d}	20.10 ± 0.98^{c}	15.52 ± 0.41^{c}	3.18 ± 0.2^{c}
F4	76.94 ± 0.28^{e}	1.33 ± 0.08^{e}	18.42 ± 0.39^{b}	17.85 ± 0.12^{d}	3.61 ± 0.09^{d}

Results are expressed as mean ± standard deviation. Values within the same column followed by different superscript letters are significantly different ($p < 0.05$)

The incorporation of seaweed into the snack formulations had a clear effect on colour parameters (Table 4). The F0 was very light (L* = 90.85 ± 0.20) with slightly negative a* values, indicating a greenish tone, and the highest b* values, reflecting yellowness (Table 4).

With increasing seaweed addition, snack lightness (L*) significantly decreased from 90.85 in F0 to 76.94 in F4, indicating significant darkening of the products. A comparable reduction was reported for maize tortillas enriched with *Macrocystis pyrifera*, where L* decreased from 85.72 in the control to 65.53 at 9% seaweed incorporation [45]. The a* values shifted from − 1.66 (F0) to positive values (1.33 in F4), indicating the color change from a slight greenish towards reddish hues with the increasing seaweed addition. In maize tortillas enriched with brown seaweed, a* values also significantly changed with increasing seaweed concentration (from 0.14 to − 2.35) confirming that algal pigments substantially modify chromatic coordinates depending on matrix and formulation [45]. At the same time, yellowness b* values decreased from 29.18 in F0 to 18.42 (F4) − 20.10 (F3). In maize tortillas, b* ranged from 16.91 in the control to 18.71 at 9% inclusion, demonstrating that brown seaweed incorporation consistently alters the yellow–blue axis of cereal-based systems [45]. The total color difference (ΔE) in the presented study ranged between 12.64 (F1) and 17.85 (F4) confirmed these shifts, with values far above the threshold for visual perception (ΔE > 3), indicating that all seaweed-based formulations (F1-F4) were clearly different from the F0. Similar ΔE values were reported in maize tortillas enriched with *Macrocystis pyrifera*, where ΔE increased from 12.48 at 3% inclusion to 20.40 at 9% incorporation [45]. Even more pronounced differences were observed in Spirulina-enriched extruded snacks, where L* decreased from 63.39 to 34.13 and ΔE reached 30.50, confirming that algal pigments strongly influence color development in extruded cereal matrices [8]. Browning index (BI) significantly increased with seaweed content, from 1.85 in the F0 to 3.61 in the F4, reflecting both the contribution of algal pigments and intensified non-enzymatic browning reactions during extrusion. Brown algae contain fucoxanthin and other pigments that contribute to darker and brownish tones, which explains the lower L* and higher BI values [46]. Similar decreases in L* and changes in a* and b* were reported in gluten-free pasta fortified with *Laminaria ochroleuca* [47]. In other studies, the use of fruit pomace or spices during extrusion increased browning and reduced lightness, supporting the observation that functional ingredients with bioactive compounds often lead to darker products with higher BI values [33, 48].

3.3 Textural properties of extruded snack

Textural parameters, particularly hardness and crispness, are critical for evaluating snack quality. These attributes are closely related to the product's physical structure (density, porosity, expansion) and play a key role in consumer acceptance [49]. The results of the textural properties are presented in Table 5.

The hardness of the snack product is defined as the maximum force required to cause the first fracture of the sample, expressed in Newtons (N). Higher values of maximum force required for compression indicate higher sample hardness. Lower hardness values are desirable properties of flips products [26]. It is important to note the number of peaks during the diametrical compression test of the sample. The number of peaks represents the total number of fractures of the sample cell walls during compression, and is a non-unit size [25]. Textural properties of the extruded snacks revealed clear differences

Table 5 Textural properties of different formulations of extruded snacks

Formulation	Hardness (*N*)	Number of fracture	Crispiness work (Nmm)	Crispiness index (x 10^{-3})
F0	33.22 ± 2.21^{a}	54.80 ± 9.73^{a}	4.03 ± 0.94^{a}	9.99 ± 3.94^{a}
F1	43.54 ± 1.83^{b}	54.00 ± 2.83^{a}	4.08 ± 0.3^{a}	8.22 ± 2.0^{a}
F2	44.95 ± 2.13^{b}	55.40 ± 4.04^{a}	4.18 ± 0.35^{a}	6.91 ± 1.08^{a}
F3	52.72 ± 2.99^{c}	53.67 ± 5.39^{a}	4.73 ± 0.83^{a}	5.58 ± 1.26^{b}
F4	60.95 ± 1.04^{d}	37.00 ± 4.90^{b}	9.00 ± 1.81^{b}	2.97 ± 0.52^{c}

Results are expressed as mean ± standard deviation. Values within the same column followed by different superscript letters are significantly different ($p < 0.05$)

among the formulations. Hardness significantly increased with the increasing level of seaweed in formulation, from 33.22 N in F0 to 60.95 N in F4. This trend indicated that the increasing level of seaweed yielded denser structures, requiring greater force to fracture. The number of fractures remained relatively stable across formulations from F0 to F3 (around 54), but significantly decreased in F4, suggesting a less open and more compact internal structure of F4. These trends were confirmed by crispiness parameter. While crispiness work significantly increased in F4 (9.00 Nmm compared to ~ 4.0 Nmm in F0-F3), the crispiness index significantly decreased, reaching the lowest value in F4 (2.97×10^{-3}). A higher crispiness work together with a lower crispiness index indicated that the F4 required more energy to generate acoustic signals, but produced fewer and less intense fracture events. This indicated harder, less crispy texture compared with the formulations with lower level of seaweed inclusion. These results are consistent with the well-established relationship between hardness, expansion, and porosity in extruded snacks: increased hardness and reduced crispiness often reflect lower expansion and reduced cell wall fragility [49]. Previous studies have reported comparable structural and textural changes in snacks due to fiber enrichment, as fibers can interfere with starch gelatinization and limit product expansion [34, 50]. For example, incorporation of 10–20% dietary fiber into lentil-based extrudates significantly increased hardness and reduced the expansion index ($P \leq 0.05$), with microstructural analysis revealing thicker cell walls and smaller cell structures [34]. Similarly, starch-based extrudates enriched with up to 32% cereal bran showed a progressive decrease in porosity accompanied by an increase in maximum stress, confirming the inverse relationship between expansion and hardness [50]. These structural changes are commonly attributed to fiber interference with starch gelatinization, melt viscosity and bubble growth during expansion.

3.4 Techno-functional properties of extruded snack

WSI is associated with the presence of water-soluble components and the extent of starch dextrinization, whereas WAI reflects the capacity of starch to absorb water and is often used as an indicator of gelatinization [51]. The water solubility index (WSI) and water absorption index (WAI) of the extruded corn-based snacks fortified with *Alaria esculenta* and *Saccharina latissima* did not differ significantly across formulations (ANOVA, $p < 0.05$). WSI ranged from 26.44 ± 3.60% for the F2 to 31.36 ± 1.67% for the F0, while WAI values varied narrowly, from 5.59 ± 0.30 g/g in the F4 to 6.66 ± 0.68 g/g in the F1. These outcomes suggested that inclusion of algal biomass up to 15% did not disrupt key techno-functional properties related to starch transformation, namely starch dextrinization (WSI indicator) and gelatinization capacity (WAI indicator). The consistency of these indices across treatments indicated that the fundamental hydration and solubility characteristics of the extrudates were preserved despite fortification with

mineral-rich seaweeds. This findings are consistent with the results of Singha et al. [19], who investigated corn-based extrudates enriched with food-grade distillers dried grains (FDDG). In their study, WAI values ranged between 5.02 and 6.97 g/g dry solid, while WSI values varied from 7.85 to 14.75%, depending on formulation and processing conditions. Although the incorporation of fiber-rich FDDG significantly influenced hydration indices under specific extrusion settings, the most pronounced effects were observed for expansion ratio and bulk density rather than for WAI and WSI. This behavior is comparable to the present study, where only moderate variations in hydration-related parameters were detected, whereas structural properties showed more substantial changes. High level of seaweed fiber likely disrupts the formation of a continuous starch melt matrix and impairs bubble growth during expansion, resulting in denser, less aerated products. Fibers may also compete for water, altering gelatinization behavior and melt viscosity [52]. According to general extrusion theory, non-starch components like dietary fiber act as fillers or diluents, reducing the gas-holding capacity of gelatinized starch and thereby lowering expansion [53]. The oil absorption capacity (OAC) values ranged from 2.06 to 2.14 g oil/g sample for all formulations, and statistical analysis (ANOVA, $p > 0.05$) confirmed that there were no significant differences among the control and seaweed-enriched extrudates (Table 6). Comparable behavior has been reported for rice–teff extruded blends, where OAC values ranged between 1.58 and 1.83 g/g, with no consistent trend associated with increasing teff concentration [54].

However, other studies have demonstrated that OAC may significantly decrease at higher levels of fiber incorporation. For example, Asif et al. reported a progressive reduction in OAC from 4.6 to 2.7 g/100 g when citrus pomace concentration increased from 0% to 15%, with statistically significant differences among formulations [55]. These findings indicated that the influence of fiber enrichment on oil absorption depends on matrix composition, fiber type, and structural modifications induced during extrusion. Furthermore, Asghari-pour et al. reported a statistically significant model for oil absorption index in corn-based snacks containing date kernel flour (model $p = 0.0016$), with a strong linear effect of ingredient level ($F = 46.23$, $p < 0.0001$), while also highlighting the contribution of processing variables [56]. These findings indicated that OAC behavior is governed by both formulation factors and extrusion parameters such as temperature, feed moisture, and shear. In the present study, the relatively narrow OAC range indicated that seaweed incorporation did not substantially modify the oil-binding capacity of the extruded matrix.

3.5 Correlation analysis between compositional and physical/textural properties

To better understand the relationships between composition, structure and texture, Pearson correlation coefficients were calculated across nutritional, mineral, physical,

Table 6 Techno-functional properties of different formulations of extruded snack

Formulation	WSI	WAI	OAC
F0	31.36 ± 1.67^{a}	6.63 ± 0.39^{a}	2.11 ± 0.034^{a}
F1	27.39 ± 4.24^{a}	6.66 ± 0.68^{a}	2.09 ± 0.054^{a}
F2	26.44 ± 3.6^{a}	6.45 ± 0.33^{a}	2.06 ± 0.039^{a}
F3	27.48 ± 1.96^{a}	6.04 ± 0.48^{a}	2.12 ± 0.004^{a}
F4	29.25 ± 1.11^{a}	5.59 ± 0.3^{a}	2.14 ± 0.063^{a}

Results are expressed as mean ± standard deviation. Values within the same column followed by different superscript letters are significantly different ($p < 0.05$)

Table 7 Selected Pearson correlation coefficients of key extrudate parameters

Variable 1	Variable 2	Pearson *r*
Bulk density	Expansion index	-0.99
Porosity	Expansion index	0.91
Ash	Bulk density	0.96
Ash	Expansion index	-0.99
Insoluble DF	Expansion index	-0.98
Hardness	Ash	0.97
Hardness	Insoluble DF	0.99
Crispiness index	Insoluble DF	-0.99
L*	Ash	-0.92
ΔE	Ash	0.93
BI	Hardness	0.91
Ca	Bulk density	0.95
Ca	Expansion index	-0.94
Ca	Porosity	-0.91
Mg	Bulk density	0.94
Mg	Expansion index	-0.93
Mg	Porosity	-0.90

textural and color parameters (Table 7). Several strong correlations (|r| > 0.9) were identified, highlighting the dominant role of seaweed-derived minerals and dietary fibers in shaping the structural and sensory properties of extrudates.

The analysis showed that bulk density was almost perfectly negatively correlated with expansion index (r=–0.99), and positively with ash (r = 0.96), calcium (r = 0.95) and magnesium contents (r = 0.94). Similarly, expansion index was strongly and negatively correlated with ash, insoluble dietary fibre, Ca and Mg (r=–0.93 to – 0.99), confirming that mineral- and fiber-rich additions hindered puffing during extrusion. Porosity followed the same pattern, showing negative correlations with Ca (r = – 0.91) and Mg (r = – 0.90), thus explaining the denser cellular structure observed in SEM images. In terms of texture, hardness correlated positively with ash (r = 0.97) and insoluble dietary fibre (r = 0.99), whereas crispiness index was strongly negatively correlated with insoluble dietary fiber (r=–0.99). These results demonstrate that seaweed incorporation promoted denser, harder extrudates with reduced crispiness, which is in line with the observed reduction in expansion and porosity. Color parameters also reflected compositional changes: lightness (L*) was negatively correlated with ash (r=–0.92), while both ΔE and BI increased with ash and hardness (r = 0.91–0.93), confirming that mineral- and fibre-rich formulations tend to produce darker products with stronger browning.

4 Conclusion

The present study showed that the incorporation of *Saccharina latissima* and *Alaria esculenta* into corn-based extrudates can enhance the nutritional quality of the product, particularly at inclusion levels up to 10%, without major negative effects on physical properties. At higher concentrations, structural changes became more evident, suggesting that both formulation and extrusion conditions need to be carefully adjusted.

These results support the growing interest in brown seaweeds as functional ingredients in cereal-based foods and highlight the importance of balancing nutritional improvement with acceptable texture and structure. Special attention should be paid to

mineral composition, especially sodium and iodine, when developing such products for regular consumption.

From a practical point of view, the findings provide useful information for the development of seaweed-enriched extruded snacks based on sustainable marine resources. Further research should include iodine determination, consumer sensory evaluation, and optimization of processing conditions, as well as studies on shelf-life and product stability.

Acknowledgements
This study was supported by the IMPRESS project, co-funded under the Horizon Europe programme (GA 101084437). B. Filipčev and S. Vidosavljević were supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Contract No. 451-03-136/2025-03/200222, while J. Kojić was supported under Contract No. 451-03-136/2025-03/200358.

Plant material
Collection of the plant materials used in this study complied with local or national guidelines.

Author contributions
V.B. wrote original draft, conducted analysis and prepared figures; J.K conducted analysis; B.F. validated methodology and conducted analysis; N.M. conducted analysis and data curation; V.S. and S.V. conducted analysis; B.T. and M.P. developed the concept and provided supervision; All authors reviewed the manuscript.

Funding
This study was supported by the IMPRESS project, co-funded under the Horizon Europe programme (GA 101084437). B. Filipčev and S. Vidosavljević were supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Contract No. 451-03-136/2025-03/200222, while J. Kojić was supported under Contract No. 451-03-136/2025-03/200358.

Data availability
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Milica Pojić declares that she is an Editorial Board Member of Discover Food. Prior to submission, the journal was contacted regarding the possibility of submitting a manuscript as an Editorial Board Member and confirmation was received that submission was permitted. The author confirms that she was not involved in the editorial handling or decision-making process for this manuscript.

Received: 27 November 2025 / Accepted: 9 April 2026
Published online: 22 April 2026

References

1. Luo S, Singh R, Kadam A. Koksel FBT-A in F and NR. Innovations in extruded products with improved nutritional quality. Academic; 2025. https://doi.org/10.1016/bs.afnr.2025.06.001.
2. Duque-Estrada P, Hardiman K, Bøgebjerg Dam A, Dodge N, Aaslyng MD, Petersen IL. Protein blends and extrusion processing to improve the nutritional quality of plant proteins. Food Funct. 2023;14:7361–74. https://doi.org/10.1039/D2FO03912E.
3. Nikmaram N, Leong SY, Koubaa M, Zhu Z, Barba FJ, Greiner R, et al. Effect of extrusion on the anti-nutritional factors of food products: An overview. Food Control. 2017;79:62–73. https://doi.org/10.1016/j.foodcont.2017.03.027.
4. Cebrián-Lloret V, Martínez-Abad A, Recio I, López-Rubio A, Martínez-Sanz M. In vitro digestibility of proteins from red seaweeds: Impact of cell wall structure and processing methods. Food Res Int. 2024;178:113990. https://doi.org/10.1016/j.foodres.2024.113990.
5. Tas AA, Shah AU. The replacement of cereals by legumes in extruded snack foods: Science, technology and challenges. Trends Food Sci Technol. 2021;116:701–11. https://doi.org/10.1016/j.tifs.2021.08.016.
6. Njike VY, Smith TM, Shuval O, Shuval K, Edshteyn I, Kalantari V, et al. Snack food, satiety, and weight. Adv Nutr. 2016;7:866–78.
7. Demarco M, Oliveira de Moraes J, Matos ÂP, Derner RB, de Farias Neves F, Tribuzi G. Digestibility, bioaccessibility and bioactivity of compounds from algae. Trends Food Sci Technol. 2022;121:114–28. https://doi.org/10.1016/j.tifs.2022.02.004.
8. Lucas BF, de Morais MG, Santos TD, Costa JAV. Spirulina for snack enrichment: Nutritional, physical and sensory evaluations. LWT. 2018;90:270–6. https://doi.org/10.1016/j.lwt.2017.12.032.

9. Pandey VK, Singh P, Srivastava S, Zanwar S, Dar AH, Singh R, et al. Box–Behnken design based statistical modelling to study the effects of spirulina (Arthrospira platensis) incorporation on nutritional standards of vegan snack product. J Agric Food Res. 2023;14:100700. https://doi.org/10.1016/j.jafr.2023.100700.
10. da Silva PC, Toledo T, Brião V, Bertolin TE, Costa JAV. Development of extruded snacks enriched by bioactive peptides from microalga Spirulina sp. LEB 18. Food Biosci. 2021;42:101031. https://doi.org/10.1016/j.fbio.2021.101031.
11. Caporgno MP, Mathys A. Trends in microalgae incorporation into innovative food products with potential health benefits. Front Nutr. 2018;5:58.
12. Uribe-Wandurraga ZN, Igual M, García-Segovia P, Martínez-Monzó J. Influence of microalgae addition in formulation on colour, texture, and extrusion parameters of corn snacks. Food Sci Technol Int. 2020;26:685–95.
13. Cian RE, Caballero MS, Sabbag N, González RJ, Drago SR. Bio-accessibility of bioactive compounds (ACE inhibitors and antioxidants) from extruded maize products added with a red seaweed Porphyra columbina. LWT - Food Sci Technol. 2014;55:51–8. https://doi.org/10.1016/j.lwt.2013.08.011.
14. Singh CB, Hassan MA, Gudipati V, Deshmukhe G, Xavier KAM, Balange AK. Extruded snacks fortified with seaweed (Ulva lactuca): process optimization by response surface methodology. J Env Bio-Sci. 2016;30:289–97.
15. Jayakody MM, Vanniarachchy MPG. Chapter 13 - Seaweed-derived snack foods: products and processing. In: Hefft DI, editor Adetunji COBT-A of S in F and N, editors., Elsevier: Amsterdam; 2024, pp. 215–24. https://doi.org/10.1016/B978-0-323-91803-9.00010-X
16. Nielsen CW, Holdt SL, Sloth JJ, Marinho GS, Sæther M, Funderud J, et al. Reducing the high iodine content of Saccharina latissima and improving the profile of other valuable compounds by water blanching. Foods. 2020;9:569.
17. Kojić JS, Ilić NM, Kojić PS, Pezo LL, Banjac VV, Krulj JA, et al. Multiobjective process optimization for betaine enriched spelt flour based extrudates. J Food Process Eng. 2019;42:e12942. https://doi.org/10.1111/jfpe.12942.
18. Vallée M, Lu X, Narciso JO, Li W, Qin Y, Brennan MA, et al. Physical, predictive glycaemic response and antioxidative properties of black ear mushroom (Auricularia auricula) extrudates. Plant Foods Hum Nutr. 2017;72:301–7.
19. Singha P, Singh SK, Muthukumarappan K, Krishnan P. Physicochemical and nutritional properties of extrudates from food grade distiller's dried grains, garbanzo flour, and corn grits. Food Sci Nutr. 2018;6:1914–26. https://doi.org/10.1002/fsn3.769.
20. Omoba OS, Olagunju AI, Oluwajuyitan TD, Akinrinlola OF. Functional extruded snacks from amaranth, soycake and shallot flours: Nutritional composition, physicochemical and antioxidant properties. Meas Food. 2024;15:100194. https://doi.org/10.1016/j.meafoo.2024.100194.
21. Pojić M, Musse M, Rondeau C, Hadnađev M, Grenier D, Mariette F, et al. Overall and Local Bread Expansion, Mechanical Properties, and Molecular Structure During Bread Baking: Effect of Emulsifying Starches. Food Bioprocess Technol. 2016;9:1287–305. https://doi.org/10.1007/s11947-016-1713-2.
22. Gostick JT, Khan ZA, Tranter TG, Kok MDR, Agnaou M, Sadeghi M, et al. PoreSpy: A python toolkit for quantitative analysis of porous media images. J Open Source Softw. 2019;4:1296.
23. Bokić J, Kojić J, Krulj J, Pezo L, Banjac V, Škrobot D, et al. Development of a novel rice-based snack enriched with chicory root: physicochemical and sensory properties. Foods. 2022;11:2393.
24. Höglund E, Eliasson L, Oliveira G, Almli VL, Sozer N, Alminger M. Effect of drying and extrusion processing on physical and nutritional characteristics of bilberry press cake extrudates. LWT - Food Sci Technol. 2018;92:422–8. https://doi.org/10.1016/j.lwt.2018.02.042.
25. Alam SA, Pentikäinen S, Närväinen J, Katina K, Poutanen K, Sozer N. The effect of structure and texture on the breakdown pattern during mastication and impacts on in vitro starch digestibility of high fibre rye extrudates. Food Funct. 2019;10:1958–73. https://doi.org/10.1039/c8fo02188k.
26. Arivalagan M, Manikantan MR, Yasmeen AM, Sreejith S, Balasubramanian D, Hebbar KB, et al Physiochemical and nutritional characterization of coconut (Cocos nucifera L.) haustorium based extrudates. Volume 89. Elsevier Ltd: Amsterdam;; 2018. . https://doi.org/10.1016/j.lwt.2017.10.049.
27. Kostić M, Omerović N, Ilić D, Brkić B, Filipović V, Terzić M et al. Pectin-based pH-sensitive films incorporating cold-pressed elderberry juice for chicken freshness monitoring. J Food Meas Charact. 2026. https://doi.org/10.1007/s11694-025-03943-x
28. Lazou A, Krokida M. Functional properties of corn and corn–lentil extrudates. Food Res Int. 2010;43:609–16. https://doi.org/10.1016/j.foodres.2009.09.017.
29. Kalahal SP, Gavahian M, Lin J. Development of innovative tigernut-based nutritional snack by extrusion process: effects of die temperature, screw speed, and formulation on physicochemical characteristics. Qual Assur Saf Crop Foods. 2024;16:1–22.
30. Healy LE, Zhu X, Pojić M, Sullivan C, Tiwari U, Curtin J, et al. Biomolecules from macroalgae—nutritional profile and bioactives for novel food product development. Biomolecules. 2023;13:386.
31. Jacobsen M, Bianchi M, Trigo JP, Undeland I, Hallström E, Bryngelsson S. Nutritional and toxicological characteristics of Saccharina latissima, Ulva fenestrata, Ulva intestinalis, and Ulva rigida: a review. Int J Food Prop. 2023;26:2349–78.
32. Lytou AE, Schoina E, Liu Y, Michalek K, Stanley MS, Panagou EZ, et al. Quality and safety assessment of edible seaweeds Alaria esculenta and Saccharina latissima cultivated in Scotland. Foods. 2021;10:2210.
33. Amer SA, Rizk AE. Production and evaluation of novel functional extruded corn snacks fortified with ginger, bay leaves and turmeric powder. Food Prod Process Nutr. 2022;4:4. https://doi.org/10.1186/s43014-022-00083-3.
34. Sinaki NY, Koksel F. Effects of dietary fibre source and content and extrusion conditions on the physicochemical composition and physical quality of fibre-enriched lentil snacks. Int J Food Sci Technol. 2024;59:2236–48. https://doi.org/10.1111/ijfs.16943.
35. Circuncisão AR, Catarino MD, Cardoso SM, Silva AMS. Minerals from macroalgae origin: Health benefits and risks for consumers. Mar Drugs. 2018;16:400.
36. Diop M, Ndiaye C, Lubaale J, Sé A, Gaye ML, Traoré D. Application of Extrusion Cooking to Enhancing Mineral Bioaccessibility in Millet Flour Enriched with Natural Fortificants for Vulnerable Populations. Food Nutr Sci. 2024;15:1357–80.
37. Shah F-H, Sharif MK, Ahmad Z, Amjad A, Javed MS, Suleman R, et al. Nutritional characterization of the extrusion-processed micronutrient-fortified corn snacks enriched with protein and dietary fiber. Front Nutr. 2022;9:1062616.
38. Holdt SL, Kraan S. Bioactive compounds in seaweed: functional food applications and legislation. J Appl Phycol. 2011;23:543–97. https://doi.org/10.1007/s10811-010-9632-5.

39. Wells ML, Potin P, Craigie JS, Raven JA, Merchant SS, Helliwell KE, et al. Algae as nutritional and functional food sources: revisiting our understanding. J Appl Phycol. 2017;29:949–82. https://doi.org/10.1007/s10811-016-0974-5.
40. Ali IM, Forsido SF, Kuyu CG, Ahmed EH, Andersa KN, Chane KT, et al. Effects of extrusion process conditions on nutritional, anti-nutritional, physical, functional, and sensory properties of extruded snack: A review. Food Sci Nutr. 2024;12:8755–61.
41. Chen J, Liu Q, Zhao S, Guo L, Zhuang X, Chen X, et al. Effect of extrusion processing on the structural, functional, and physicochemical properties of wheat and wheat-based products: A review. Food Phys. 2025;2:100050. https://doi.org/10.1016/j.foodp.2025.100050.
42. Robin F, Schuchmann HP, Palzer S. Dietary fiber in extruded cereals: Limitations and opportunities. Trends Food Sci Technol. 2012;28:23–32. https://doi.org/10.1016/j.tifs.2012.06.008.
43. Skamniotis CG, Patel Y, Elliott M, Charalambides MN. Toughening and stiffening of starch food extrudates through the addition of cellulose fibres and minerals. Food Hydrocoll. 2018;84:515–28. https://doi.org/10.1016/j.foodhyd.2018.06.004.
44. Aghajanzadeh S, Sultana A, Mohammad Ziaiifar A, Khalloufi S. Formation of pores and bubbles and their impacts on the quality attributes of processed foods: A review. Food Res Int. 2024;188:114494. https://doi.org/10.1016/j.foodres.2024.114494.
45. Pérez-Alva A, Baigts-Allende DK, Ramírez-Rodrigues MA, Ramírez-Rodrigues MM. Effect of brown seaweed (Macrocystis pyrifera) addition on nutritional and quality characteristics of yellow, blue, and red maize Tortillas. Foods. 2022;11:2627.
46. Din NAS, Mohd Alayudin 'Ain Sajda, Sofian-Seng N-S, Rahman HA, Mohd Razali NS, Lim SJ et al. Brown algae as functional food source of fucoxanthin: a review. Foods. 2022;11:2235.
47. Fradinho P, Raymundo A, Sousa I, Domínguez H, Torres MD. Edible brown seaweed in gluten-free pasta: Technological and nutritional evaluation. Foods. 2019;8:622.
48. Borah A, Lata Mahanta C, Kalita D. Optimization of process parameters for extrusion cooking of low amylose rice flour blended with seeded banana and carambola pomace for development of minerals and fiber rich breakfast cereal. J Food Sci Technol. 2016;53:221–32. https://doi.org/10.1007/s13197-015-1772-9.
49. Alam MS, Kaur J, Khaira H, Gupta K. Extrusion and Extruded Products: Changes in Quality Attributes as Affected by Extrusion Process Parameters: A Review. Crit Rev Food Sci Nutr. 2016;56:445–73. https://doi.org/10.1080/10408398.2013.779568.
50. Chanvrier H, Desbois F, Perotti F, Salzmann C, Chassagne S, Gumy J-C, et al. Starch-based extruded cereals enriched in fibers: A behavior of composite solid foams. Carbohydr Polym. 2013;98:842–53. https://doi.org/10.1016/j.carbpol.2013.07.005.
51. Oikonomou NA, Krokida MK. Literature Data Compilation of WAI and WSI of Extrudate Food Products. Int J Food Prop. 2011;14:199–240. https://doi.org/10.1080/10942910903160422.
52. Nur Adibah L, Nor Afizah M, Wan Zunairah W, Syed Muhammad S. Development of fibre-rich okara-based expanded snack via single screw extrusion. Food Res. 2024;8:48–56.
53. Anand A, Dhaliwal YS, Verma R. A Review on Food Extrusion Its Classification and Quality Attributes. Ind J Pure App Biosci. 2020;8:707–14.
54. Martín-Diana AB, Blanco Espeso B, Jimenez Pulido IJ, Acebes Martínez PJ, Rico D. Twin-screw extrusion as hydrothermal technology for the development of gluten-free teff flours: effect on antioxidant, glycaemic index and techno-functional properties. Foods. 2022;11:3610.
55. Asif M, Khan MKI, Khan MI, Maan AA, Helmick H, Kokini JL. Effects of citrus pomace on mechanical, sensory, phenolic, antioxidant, and gastrointestinal index properties of corn extrudates. Food Biosci. 2023;55:103012. https://doi.org/10.1016/j.fbio.2023.103012.
56. Asghari-pour S, Noshad M, Nasehi B, Jooyandeh H, Beiraghi-Toosi S. Optimization of physicochemical and functional properties of corn-based snacks containing date kernel flour. J Food Process Preserv. 2018;42:e13821. https://doi.org/10.1111/jfpp.13821.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.