



Type of the Paper (Article)

Physicochemical, textural, and sensory properties of wheat-based crackers substituted with tilapia (*Oreochromis niloticus*) and green seaweed (*Ulva lactuca*) flours

Nani Ratnaningsih^{1*}, Badraningsih Lastariwati¹ and Arum Widyastuti Perdani²

¹ Department of Culinary Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Kampus Karangmalang, Yogyakarta 55281, Indonesia

² Department of Culinary Vocational, Faculty of Vocational, Universitas Negeri Yogyakarta, Kampus Gunungkidul, Yogyakarta 55893, Indonesia

Abstract

Crackers are a popular snack made from wheat flour that is low in protein and minerals. Tilapia (*Oreochromis niloticus*) and green seaweeds, such as *Ulva lactuca*, contain high protein and minerals that can prevent nutritional deficiencies in children; however, their application in bakery products remains a challenge. The objective of research was to evaluate the physicochemical, texture, and sensory characteristics of wheat-based crackers (F0) with the substitution of 25% tilapia flour (F1) and the addition of 1-3% *Ulva lactuca* flour (F2, F3, F4). Protein and iron content of tilapia crackers (F1) were increased by 98% and 18%, respectively, compared to F0. Furthermore, adding *Ulva lactuca* flour to tilapia crackers enhanced protein and iron content by 111-122 % and 63-89 %, respectively, compared to F0. Substitution of tilapia and *Ulva lactuca* flours also increased the browning index, cohesiveness, adhesiveness, crispiness, and resilience but decreased the lightness (L*), a*, and b*, hardness, and crunchiness of crackers. However, the higher addition of *Ulva lactuca* decreased the physicochemical, color, texture properties, and sensory acceptance. Tilapia crackers with the addition of 1% *Ulva lactuca* contain 23.06 ± 0.05 g/100 g of protein and 7.57 ± 0.27 mg/100 g of iron and are more preferred than other formulations, suggesting a high in protein and iron snack for children.

Article History

Received June 4, 2025

Accepted March 10, 2026

Published April 2, 2026

Keywords

Wheat-based
Crackers, Tilapia,
Ulva lactuca,
Physicochemical,
Textural Properties.

1. Introduction

Currently, aquatic-based foods are getting more attention for their critical role in food security and nutrition, not only as a source of protein, but also as a source of essential omega-3 fatty acids and micronutrients such as iron, zinc, and calcium (1). According to the report of the Food and Agriculture Organization (2), in 2022 total fisheries and aquaculture production hit a new high of 223.2 million tonnes consisting of 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae, owing largely to the rise of aquaculture, particularly in Asia which contribute approximately 70% of the total. China is the major producer with a share of 35% of the total, followed by India (8%), Indonesia (7%), Viet Nam (5%), and Peru (3%) (3).

Indonesia is an archipelago country with two-thirds of the country's area in the form of water thus fishery production is abundant. In 2024, Indonesia produced a total fisheries and aquaculture of 23.56 million tonnes including 7.81 million tonnes of capture fisheries and 15.75 million tonnes of aquaculture (4). Indonesia is also known as the second-world producer of algae after China with a contribution of 27% of 36 million tonnes (wet weight) of

* Correspondence: Nani Ratnaningsih  nani_ratnaningsih@uny.ac.id

algae (3) with approximately 9.85 million tonnes (5). Green seaweed or sea lettuce (*Ulva lactuca*) is one of the algae found in Indonesia which contains high carbohydrates, protein, ash, and low fat. *Ulva lactuca* also contains sulfated polysaccharides, known as ulvan, that can be utilized as bioactive compounds in food products (6).

Nile tilapia (*Oreochromis niloticus*) is the third major aquaculture species in the world with total world production of 4.41 million tonnes in 2020 (3) due to its rapid growth, resistance to diseases, good tolerance to various environmental conditions, high marketability, good taste, low-fat content, and lack of muscle spines (6,7). In Indonesia, tilapia is also the major aquaculture species with total production of 1.56 million tonnes in 2024 (5). Tilapia contains high protein (20-35%), low fat (1-2%), 23 fatty acids including omega-3 polyunsaturated fatty acids, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), and minerals such as calcium, phosphorus, magnesium, sodium, and iron (9).

Fish processing, such as tilapia flour, is needed to increase shelf life and economic values and to supply consumers with a nutritious, more stable shelf life, and convenient foods (1). Tilapia flour has been reported as an ingredient to increase macro- and micronutrients in various food products, including extruded snacks (10), bread (11), pasta (12), snack bar (13), tapioca cookies (9), cookies (14), and biscuit (15). Tilapia flour has great potential as a protein and mineral source in snack products, such as crackers. Crackers have been known as a popular snack in the world since 150 years ago (16). Crackers can be defined as thin and crisp products baked from unsweetened and unleavened dough (17). Despite their popularity, crackers are made primarily from wheat flour, which is deficient in protein and minerals. To the best of our knowledge, the incorporation of tilapia flour in wheat-based crackers remains challenging.

Nowadays, the demand for healthy snacks is growing because of the change in preference consumers for food products containing health-promoting ingredients. Mondelez International reported consumers prefer snack foods with high protein and dietary fiber, but low in fat, sugar, cholesterol, salt, and calories (18). However, commercial snack foods on the market in Indonesia were dominated by those high in fat, sugar, and calories, while poor in protein and mineral content (19). Protein and minerals, such as iron, are nutrients vital for optimal growth in children and teenagers. Deficiency of protein and iron in children and teenagers may contribute to the impairment of physical, cognitive, and immune development (20). Institute of Medicine recommended dietary intake of iron is 8-11 mg and 8-18 mg for men and women above 9 years of age, respectively (21).

Previous studies have reported the development of wheat-based crackers with high protein and mineral content through substitution with various fish and seaweeds, such as tuna bone powder (22), microalgae (23), salmon frame (24), jellyfish (16), carcass tilapia flour (9), green seaweeds (*Ulva lactuca* and *Ulva fasciata*) (25), largehead hairtail (*Trichiurus lepturus*) fish flour (26), red seaweed (27), *Ulva* sp. (28), anchovy and *Ulva lactuca* (29), and *Gracilaria tenuistipitata* (30). However, the development of wheat-based crackers made by incorporation of tilapia and *Ulva lactuca* flours has not yet been investigated. In the present study, we evaluated the physicochemical and textural properties, and also sensory acceptance of wheat-based crackers substituted with tilapia and *Ulva lactuca* flours. We also analyzed the principal component analysis to understand the impact of the incorporation of tilapia and *Ulva lactuca* flours on the physicochemical, textural, and sensory acceptance of crackers. The study's findings could lead to the development of a nutritious snack with higher

protein and iron content for prevention nutritional deficiencies in children, particularly in Indonesia.

2. Materials and Methods

2.1. Materials

Fresh tilapia fish were obtained from local fish farmers in Sleman District, Province of Special Region of Yogyakarta, Indonesia. The specification of tilapia fish is red tilapia fish (*Oreochromis niloticus*) with a weight range of 500-600 grams. Semi-dried green seaweeds (*Ulva lactuca*) were obtained from seaweed collectors in Gunungkidul District, Province of Special Region of Yogyakarta, Indonesia. The other ingredients of crackers were purchased from a local market, such as wheat flour (medium protein content, Segitiga Biru), margarine (Blueband), corn starch (Maizenaku), yeast (Fermipan), mushroom broth powder (Totole), garlic powder (Koepoe-koepoe), baking powder (Koepoe-koepoe), skim milk (Dancow), and salt (Refina).

The equipment in the crackers making included cabinet dryer, grinder (Fomac FGD-Z200, Putra Chandra Sentosa Co., Ltd., Jakarta, Indonesia), sieve (Retsch sieve 80 mesh), stainless steel bowl, bowl mixer (4.8 L bowl-lift stand mixer, KitchenAid, Benton Harbor, MC, USA), dough sheeter (Fomac NOD-200S, Putra Chandra Sentosa Co., Ltd., Jakarta, Indonesia), stainless steel crackers mold, and gas oven (Fomac BOV-ARF20H, Putra Chandra Sentosa Co., Ltd., Jakarta, Indonesia).

2.2. Preparation of tilapia dan *Ulva lactuca* flour

Tilapia flour was prepared as following procedures. Fresh red tilapia fish was eviscerated and descaled, and the head, tail, and fins were removed. Furthermore, the fish is split on the back and the meat is taken and then washed using clean water until there are no dirt and blood. The next step is to soak the tilapia fillets in a lime solution (50 mL of lime juice dissolved in 1 L of water) for 10-15 min, rinsed with water, steamed at 85–90 °C for 15-20 min, and then the fish's meat is separated from the bones and skin. After that, the fish meat was dried using a cabinet dryer at a temperature of 50 °C for 24 hours. The dried fish meat was ground using a grinder and sieved through a 80-mesh sieve.

Ulva lactuca flour was prepared as following procedures. The semi-dried *Ulva lactuca* seaweeds were washed with running water to remove impurities such as sand and other impurities. The next step is blanching the seaweed at 90 °C for 3-5 minutes to remove the fishy smell and soften the seaweed. After that, the seaweed is rinsed under running water, drained, chopped roughly, and dried using a cabinet dryer at 50 °C for 24 h. The dried seaweed was ground with a grinder and sieved through a 20-mesh sieve.

2.3. Preparation of crackers

Wheat-based crackers formulation consists of wheat flour, margarine, yeast, corn starch, garlic powder, mushroom broth powder, skim milk, baking powder, salt, and water (Table 1). We conducted preliminary research to determine the substitution of tilapia flour, i.e. 20, 25, and 30% (w/w) based on the weight of wheat flour, in wheat-based crackers (unpublished work). The sensory test found that the substitution of 25% tilapia flour was preferred by ten trained panelists due to the best color, flavor, taste, and texture acceptability. Therefore, formulation of wheat-based crackers used the substitution of tilapia flour at 25% (w/w) based on the weight of wheat flour. The addition of 1%, 2%, and 3% (w/w)

Ulva lactuca flour in the tilapia crackers formulation was conducted based on the weight of wheat and tilapia flour.

Dry ingredients such as wheat flour, tilapia flour, yeast, corn starch, garlic powder, mushroom broth powder, skim milk, baking powder, and salt were mixed in a bowl mixer (4.8 L bowl-lift stand mixer, KitchenAid, Benton Harbor, MC, USA) for 2 min. Thereafter, *Ulva lactuca* flour, melted margarine, and water were added and mixed at low speed for 3 min. The amount of water added for F0 and F1 is same; however, for F2, F3, and F4 are different with F0 and F1 due to obtain the desired dough texture. The cracker dough was wrapped using plastic wrap and rested at room temperature (25-28 °C) for 45 min. The resulting cracker dough was sheeted to a thickness of 2 mm and cut into a rectangle (4.0 x 5.5 cm²) using a stainless-steel cracker mold. The shaped cracker dough was placed on a baking tray and baked in a gas oven (Fomac BOV-ARF20H, Putra Chandra Sentosa Co., Ltd., Jakarta, Indonesia) at 180 °C for 8 min. The crackers were cooled at room temperature (25-28 °C) and stored in an airtight jar for 24 h before further analysis.

Table 1. Ingredients of tilapia and *Ulva lactuca* crackers.

Ingredient	F0		F1		F2		F3		F4	
	g	%	g	%	g	%	g	%	g	%
Wheat flour	200	54.5	150	40.9	150	38.6	150	38.4	150	38.2
Tilapia flour	0	0.0	50	13.6	50	12.9	50	12.8	50	12.7
<i>Ulva lactuca</i> flour	0	0.0	0	0.0	2	0.5	4	1.0	6	1.5
Water	80	21.8	80	21.8	100	25.7	100	25.6	100	25.4
Margarine	75	20.4	75	20.4	75	19.3	75	19.2	75	19.1
Yeast	3	0.8	3	0.8	3	0.8	3	0.8	3	0.8
Corn starch	2	0.5	2	0.5	2	0.5	2	0.5	2	0.5
Mushroom broth powder	2	0.5	2	0.5	2	0.5	2	0.5	2	0.5
Garlic powder	2	0.5	2	0.5	2	0.5	2	0.5	2	0.5
Skim milk	1	0.3	1	0.3	1	0.3	1	0.3	1	0.3
Baking powder	1	0.3	1	0.3	1	0.3	1	0.3	1	0.3
Salt	1	0.3	1	0.3	1	0.3	1	0.3	1	0.3

Note: F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour

2.4. Analysis of nutritional composition

The nutritional composition was analyzed for their moisture (Method No. 925.09), crude protein (Nx6.25) (Method No. 920.87), total lipid (Method No. 920.39) with petroleum ether as a solvent, and ash content (Method No. 923.03) following the standard methods of AOAC (31). Iron content was analysed using dry destruction with Atomic Absorption Spectrophotometer (32).

2.5. Analysis of color

Color analysis was conducted by a Chromameter CR-400 (Konica Minolta Optics, Inc.) to determine the Hunter values of L* (lightness, L = 0 is black and L = 100 is white), a* (+a* values are redness and -a* values are greenness), and b* (+b* values are yellowness and -b* values

are blueness). Determination of chroma (C) and hue (h), using equations (1) and (2) (33). Determination of color (ΔE^*) and chroma differences (ΔC^*) were conducted using equations (3) and (4) (22), whereas the browning index (BI) was calculated based on the CIE values of L^* , a^* , and b^* using equations (5) and (6) (34).

$$\text{Chroma (C)} = \sqrt{(a^2 + b^2)} \quad (1)$$

where:

$a = +a^*$ values are redness and $-a^*$ values are greenness

$b = +b^*$ values are yellowness and $-b^*$ values are blueness

$$\text{hue (h}^0\text{)} = \arctan\left(\frac{b}{a}\right) \quad (2)$$

where:

$a = +a^*$ values are redness and $-a^*$ values are greenness

$b = +b^*$ values are yellowness and $-b^*$ values are blueness

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (3)$$

Where:

ΔE^* = color differences

ΔL^* = differences between the corresponding L^* values of the sample and control crackers

Δa^* = differences between the corresponding a^* values of the sample and control crackers

Δb^* = differences between the corresponding b^* values of the sample and control crackers

$$\Delta C^* = \sqrt{\Delta a^{*2} + \Delta b^{*2}} \quad (4)$$

Where:

ΔC^* = chroma differences

Δa^* = differences between the corresponding a^* values of the sample and control crackers

Δb^* = differences between the corresponding b^* values of the sample and control crackers

$$BI = \frac{100(x-0.31)}{0.17} \quad (5)$$

$$x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (6)$$

Where:

BI = browning index

L^* = lightness value

$a^* = +a^*$ values are redness and $-a^*$ values are greenness

$b^* = +b^*$ values are yellowness and $-b^*$ values are blueness

2.6. Analysis of textural properties

Determination of the textural properties of crackers was conducted using Texture Analyzer (TA1, Lloyd Instruments) according to the method of Ratnaningsih et al. (35). Crackers ($4 \times 5 \times 0.3 \text{ cm}^3$) was pressed with a probe (load cell type of 1KN1229, diameter of 35 mm) to achieve 50% of its height. The test speed was 0.5 mm/s, wait time 0.5 s, preload/stress 1 N, and preload/stress speed 300 mm/min. Some textural parameters were observed, such as hardness, cohesiveness, adhesiveness, springiness, crispiness, crunchiness, and resilience of samples.

2.7. Sensory evaluation

The sensory evaluation of crackers was conducted by 30 semi-trained panelists (females aged 19-23 years) from students of Department of Culinary Education, Faculty of Engineering, Universitas Negeri Yogyakarta. The ethical clearance of sensory evaluation has been approved by ethics committee of Directorate of Research and Community Service, Universitas Negeri Yogyakarta in accordance to seven standards of WHO 2011, referring to the 2016 CIOMS Guidelines, with description of ethical exemption No. T/3.3/UN34.9/KP.06.07/2022. Samples were placed in plastic clips with three-digit random numbers and presented in randomized order. Panelists were given mineral water to neutralize and rinse the palate before and after the sensory evaluation of the sample. Panelists evaluated the sensory acceptance of crackers, including color, flavor, taste, texture, and overall acceptability using a five-point hedonic scale (1 = very dislike, 2 = dislike, 3 = slightly like, 4 = like, and 5 = very like).

2.8. Statistical analysis

All the experiments were performed in triplicate. Data were expressed as a mean value \pm standard deviation and then analyzed using one-way ANOVA and Duncan's multiple range test to assess significant differences among experimental mean values ($p < 0.05$) using SPSS version 26 for Windows. Principal Component Analysis (PCA) is conducted by XLSTAT software (ver 2021, Addinsoft, New York, USA).

3. Results and Discussion

3.1. Nutritional composition of tilapia and *Ulva lactuca* crackers

The nutritional composition of tilapia and *Ulva lactuca* crackers is shown in Table 2. Tilapia and *Ulva lactuca* crackers had a significantly different nutritional composition from the control. The moisture content of all crackers ranged of 3.61-4.49% (dry basis) or 3.48-4.30% (wet basis), indicating the water content of the crackers met the quality standard based on the Indonesian National Standard for biscuit (36), i.e. less than 5% (wet basis). The moisture content of the crackers was higher than crackers from tuna bone powder (1.36-2.59%) (22), jellyfish (0.97-2.19%) (16), *Ulva lactuca* incorporated crackers (2.79-3.26%) (25), and cookies from tilapia fish concentrate and red seaweed *Portieria hornemanii* (1.01-1.56%) (14). However, the moisture content remained lower than gluten-free crackers substituted with protein isolates and hydrocolloids (5.00-7.16%) (37) and extruded snacks substituted with tilapia carcass flour (7.34-8.41%) (10). Similar moisture content was also reported in semi-sweet biscuits with substitution of sea grapes (*Caulerpa racemosa*) (3.97-4.08%) (38). This result suggests that tilapia and *Ulva lactuca* flour in wheat-based crackers contribute to higher water retention than other materials mentioned in previous studies. In addition, the lower of moisture content of tilapia and *Ulva lactuca* crackers is potentially due to the hydrophilic nature of protein and polysaccharide components. The higher addition of seaweeds could contribute to weaker gluten network that is less effective to trap gas bubbles and water molecules. Moreover, it can reduce the water content of crackers as reported by Batista et al. (23). These differences in moisture content highlight the impact of ingredient composition and processing techniques on the physicochemical properties of crackers.

Substitution of tilapia and *Ulva lactuca* flours significantly increased the ash and protein content of crackers from 2.55 ± 0.03 % and 10.88 ± 0.16 % in F0 to 4.07 ± 0.05 % and 24.16 ± 0.07 % in F4, respectively. The nutritional composition of tilapia flour consists of moisture 5.40 ± 0.22 %, ash 4.06 ± 0.03 %, lipid 7.84 ± 0.08 %, protein 69.50 ± 0.20 %, and iron

43.01±0.45 mg/100 g (as dry basis). The protein content of tilapia flour showed a higher value than reported by de Souza (9), i.e. 50.55%, indicating the differences in gender of fish, fish farming method, feeding of the fish, and preparation of tilapia flour (9). Substitution of 25 % tilapia flour raised the protein content of F1 crackers by 98% compared to F0, implying that tilapia flour could potentially be utilized as a source of protein in wheat-based products. Increasing protein content of wheat-based crackers substituted by tilapia flour is higher than tilapia snack bar, i.e. from 23.91 % in control to 27.41 % in snack bar enriched with 10% tilapia dry powder (13). de Souza et al (9) reported that the protein content of tapioca cookies enhanced by substitution of 3-15 % tilapia flour, i.e. from 1.93 % to 3.35-10.29 %. Sivaraman et al (14) also reported the increase protein content of cookies substituted with 5% tilapia fish concentrate, i.e. from 4.98 % to 6.08 %.

Table 2. Nutritional composition of tilapia and *Ulva lactuca* crackers (% dry basis).

Parameter (g/100 g)	F0	F1	F2	F3	F4
Moisture	4.49 ± 0.10 ^a	4.21 ± 0.09 ^b	4.23 ± 0.08 ^b	4.18 ± 0.13 ^b	3.61 ± 0.07 ^c
Ash	2.55 ± 0.03 ^e	2.87 ± 0.05 ^d	3.33 ± 0.04 ^c	3.75 ± 0.03 ^b	4.07 ± 0.05 ^a
Protein	10.88 ± 0.16 ^e	21.59 ± 0.19 ^d	23.06 ± 0.06 ^c	23.73 ± 0.02 ^b	24.16 ± 0.07 ^a
Lipid	22.05 ± 0.06 ^c	24.63 ± 0.13 ^a	23.48 ± 0.21 ^b	23.57 ± 0.06 ^b	23.64 ± 0.05 ^b
Carbohydrate	60.02 ± 0.26 ^a	46.70 ± 0.21 ^b	45.90 ± 0.09 ^c	44.77 ± 0.12 ^d	44.53 ± 0.22 ^d
Iron (mg)	4.63 ± 0.15 ^d	5.47 ± 0.17 ^c	7.57 ± 0.27 ^b	7.87 ± 0.28 ^b	8.59 ± 0.36 ^a
Energy (Kcal)	482.06 ± 0.41 ^d	494.84 ± 1.00 ^a	487.15 ± 1.40 ^b	486.15 ± 0.51 ^b	487.51 ± 0.18 ^b

Note: F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour. Data is presented in the form of mean values ± standard deviation (n=3). Different superscripts within a row indicate significant differences among samples ($p < 0.05$).

The addition of 1-3 % *Ulva lactuca* flour increased the protein content of crackers by around 6-11 % compared with F1 crackers. *Ulva lactuca* flour contained 17.86 % of ash and 10.00 % of protein content (6), whereas Bajad et al (39) reported that *Ulva lactuca* contained 21.42 % of ash and 18.55 % of protein. The increasing protein content of crackers by the addition of *Ulva lactuca* is reported in nutri-bar, i.e. from 7.54 % in control to 7.89 % and 8.55 % in nutri-bar incorporated by 5 % and 10 % *Ulva lactuca*, respectively (40). Egodavitharana et al. (25) showed an increase protein content from 8.46 % to 10.36 % in control and substitution of 4 % *Ulva lactuca* crackers, respectively. Perdani et al. (28) also reported an increase protein content from 9.11 % to 13.84 % in control and biscuit substituted by 7 % *Ulva lactuca*. Meanwhile, crackers substituted with 20 % anchovy flour and 3 % *Ulva lactuca* flours (29) had a higher protein content (24.80 %) compared with control (11.15 %). *Ulva lactuca* contains 10-25 % protein, including nine essential amino acids (methionine, leucine, lysine, phenylalanine, arginine, isoleucine, threonine, valine, and tyrosine) (5, 36-37). In addition, the most significant amino acid in *Ulva lactuca* is aspartate and glutamate acids that affect the taste sensation of umami (41). Increasing protein content of tilapia and *Ulva lactuca* crackers contributes the reduction in their moisture content. The interaction of polysaccharides and protein via electrostatic forces enhances water entanglement, resulting in a more uniform network with a lesser amount of water, which is related to a decreased moisture content in foods with high protein and polysaccharides (43).

The lipid content of wheat-based crackers substituted by 25% tilapia flour was $24.63 \pm 0.13\%$ that was higher than FO due to the high lipid content of tilapia flour, i.e. $7.84 \pm 0.08\%$. Tilapia crackers have similar lipid content as reported in tapioca cookies (9), but lower than tilapia cookies (14). Tilapia carcass contains 23 fatty acids, including essential omega-3 fatty acids, such as polyunsaturated fatty acids (PUFAs), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (1). Meanwhile, the addition of 1-3% *Ulva lactuca* flour decreased the lipid content of crackers which is associated with low lipid and high dietary fiber content of *Ulva lactuca* (42). Otherwise, the substitution of tilapia flour decreased the carbohydrate content of wheat-based crackers as reported in extruded snacks (10), tapioca cookies (9), cookies (14), crackers (25), and biscuit (28). Addition of *Ulva lactuca* in tilapia crackers decreased carbohydrate content, which is attributed to a high content of indigestible dietary fiber and presence of ulvan complex polysaccharides of *Ulva lactuca* that are difficult to break down by digestive enzymes (39).

Iron is a vital micronutrient for the human body to provide various metabolic functions such as an oxygen carrier, synthesis of enzymes and DNA, erythropoiesis, and immune response (20). The substitution of 25% tilapia flour and the addition of 1-3% *Ulva lactuca* flour increased iron content by around 18 % and 63-89%, respectively. An increase iron content of wheat-based crackers is contributed by the iron content of Nile tilapia flour and dried *Ulva lactuca* that contains 43.01 mg/100 g and 14.0 mg/100 g (44), respectively. The iron content of wheat-based tilapia crackers was higher than cookies incorporated with tilapia fish protein concentrate and *Portieria hornemanii* seaweed (14), however, lower than biscuits from breadfruit and wheat flours enriched with catfish meal (45). Seaweeds, such as *Sargassum*, *Ulva spp*, and *Porphyra spp*, could improve iron intake from wheat and maize, probably due to high quantities of ascorbic acid which transforms iron to a more absorbable ferrous form (46). Therefore, wheat-based crackers with the substitution of tilapia flour and the addition of *Ulva lactuca* flour could be used as a healthy snack with the claim of a source of protein and iron, particularly for children, teenagers, and pregnant women.

The energy value of tilapia crackers showed a higher value than wheat-based crackers which is associated with higher protein and lipid contents. Meanwhile, addition of *Ulva lactuca* can decrease the energy value of tilapia crackers due to the lower lipid and carbohydrate content. The energy values of tilapia and *Ulva lactuca* crackers were lower than biscuits from breadfruit and wheat flours enriched catfish meal (45), snack bars enriched by 10% tilapia dry powder (13), and cookies incorporated by 2.5-10% *Portieria hornemanii* seaweed and 5% tilapia fish protein concentrate (14). However, they have higher energy value than whole wheat crackers fortified with tuna bone biocalcium (22), biocalcium and protein hydrolysate powders (3:1) from salmon frame (24), and crackers substituted with 20% anchovy and 3% *Ulva lactuca* flours (29).

3.2. Color of tilapia and *Ulva lactuca* crackers

Color is one of the food quality attributes that determine the preference of consumers, and also is associated with freshness and flavor expectation (25). Substitution of tilapia flour in wheat-based crackers significantly decreased the lightness (L^*) but increased the redness ($+a^*$), yellowness ($+b^*$), and chroma values. Moreover, the addition of *Ulva lactuca* flour decreased the L^* , greenness ($-a^*$), yellowness ($+b^*$), and chroma values, indicating the darker color of crackers (Figure 1 and Table 3). The lower L^* value of tilapia and *Ulva lactuca* crackers was associated with the higher protein content of tilapia and *Ulva lactuca* flour that promote

the Maillard browning from reaction of amino acids and reducing sugars at high temperature in baking. However, the higher addition of *Ulva lactuca* can increase the greenness ($-a^*$) and ΔC^* values as reported in crackers incorporated by 4% *Ulva lactuca* (25) and 3% *Ulva sp.* (28). Similar results were also reported in tilapia snack bars (13), jellyfish crackers (16), and cookies incorporated with tilapia fish protein concentrate and *Portieria hornemanii* seaweed (14). Incorporation of *Ulva lactuca* flour in tilapia crackers significantly increased ΔE^* and ΔC^* as reported in wheat-based crackers fortified by tuna bone bio-calcium powder (22) and bio-calcium and protein hydrolysate powder from salmon frame (24).

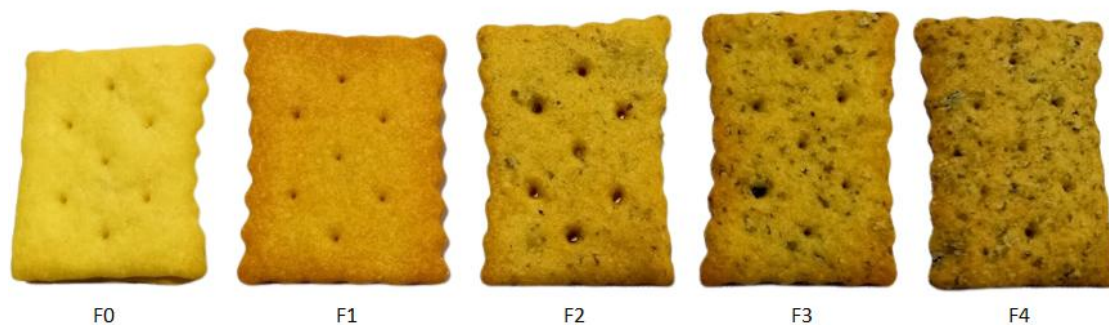


Figure 1. Appearance of crackers with substitution of tilapia flour and *Ulva lactuca* flour: F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour

The browning index (BI) represents the level of brown color and is associated with Maillard reactions (47). There are two non-enzymatic browning reactions during baking, namely Maillard reactions and caramelization, that are related to the color and flavor development of baked products (48). High temperatures during baking ($> 120\text{ }^{\circ}\text{C}$) promote the formation of acrylamide as the result of reaction between free amino acid asparagine and a carbonyl-containing compound (49). Acrylamide is categorized as probably carcinogenic to humans based on the European Food Safety Authority (EFSA) and it has a positive correlation with BI in biscuit products ($p < 0.01$) (50). The highest BI was shown by F1 and the lowest by F4. The addition of *Ulva lactuca* flour could decrease the BI of wheat-based crackers substituted by tilapia flour which is presumed by the high amino acid lysine, dietary fiber, and hydrocolloid contents of *Ulva lactuca*. The lysine content of *Ulva lactuca* might reduce acrylamide formation, whereas its hydrocolloid can form film or gel-like coatings on the cracker surface that inhibit Maillard reactions and acrylamide formation (51).

Table 3. Color of tilapia and *Ulva lactuca* crackers.

Parameter	F0	F1	F2	F3	F4
L^*	70.93 ± 0.29^a	64.51 ± 0.37^b	60.51 ± 0.41^c	57.22 ± 0.22^e	58.56 ± 0.18^d
a^*	-2.88 ± 0.03^d	4.50 ± 0.17^a	-1.71 ± 0.07^b	-2.48 ± 0.10^c	-3.24 ± 0.21^e
b^*	40.78 ± 0.12^b	43.06 ± 0.08^a	36.94 ± 0.18^c	34.46 ± 0.22^d	32.23 ± 0.35^e
C^*	40.88 ± 0.11^b	43.29 ± 0.08^a	36.98 ± 0.18^c	34.55 ± 0.23^d	32.40 ± 0.32^e
h^*	3.07 ± 0.00^b	0.10 ± 0.00^d	3.10 ± 0.00^a	3.07 ± 0.00^b	3.04 ± 0.01^c
ΔE^*	-	10.05 ± 0.37^d	11.17 ± 0.47^c	16.20 ± 0.55^a	14.58 ± 0.21^b
ΔC^*	-	7.72 ± 0.13^c	4.01 ± 0.08^d	8.61 ± 0.30^b	13.31 ± 0.46^a
BI	77.29 ± 0.13^d	115.85 ± 1.37^a	87.14 ± 1.10^b	83.17 ± 0.41^c	70.81 ± 1.95^e

Note: F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour. Data is presented in the form of mean values±standard deviation (n=3). Different superscripts within a row indicate significant differences among samples ($p < 0.05$).

3.3. Textural properties of tilapia and *Ulva lactuca* crackers

Texture is an important quality of crackers that affects the consumer's acceptance. Moreover, texture together with taste and aroma are the main factors that determine the palatability of foods (52). The textural properties of tilapia and *Ulva lactuca* crackers are presented in Table 4. The substitution of tilapia flour significantly increased the hardness, cohesiveness, crispiness, and resilience of wheat-based crackers, whereas adhesiveness and crunchiness decreased. However, the addition of *Ulva lactuca* flour significantly decreased the hardness, cohesiveness, adhesiveness, crispiness, crunchiness, and resilience of wheat-based crackers.

Hardness represents the maximum peak at the first pressure or the first bite (53). F1 crackers have a higher hardness (665.78 ± 17.97 N) than F0 (389.25 ± 7.45 N), indicating protein from tilapia flour presumably enhanced the formation of gluten network as reported in crackers enriched with fermented soybean (tempeh) paste (54). Wheat flour generates a viscoelastic gluten network, which contributes to the hardness of baked dry foods (17). Furthermore, hardness of F2, F3, and F4 exhibited a significantly decreasing around 1.81-91.98 % compared with F1, which is related to dietary fiber and hydrocolloid of *Ulva lactuca* may interact with the other proteins of ingredients to create more elastic structures that could partially mimic those created by the gluten-forming protein in wheat-based crackers (37). A similar result is reported in crackers incorporated by *Ulva lactuca* and *Ulva fasciata* (25). Dietary fiber may also prevent the proteins' interweaving and network formation by enveloping the starch granules within the cracker dough (55).

Table 4. Textural properties of tilapia and *Ulva lactuca* crackers.

Parameter	F0	F1	F2	F3	F4
Hardness (N)	389.25 ± 7.45^b	665.78 ± 17.97^a	653.73 ± 12.60^a	355.30 ± 13.90^c	53.39 ± 4.58^d
Cohesiveness	0.27 ± 0.05^e	0.64 ± 0.02^c	0.70 ± 0.03^a	0.65 ± 0.05^b	0.55 ± 0.04^d
Adhesiveness (Nmm)	4.80 ± 0.57^b	4.51 ± 0.64^b	6.92 ± 0.79^a	3.53 ± 0.03^c	1.60 ± 0.56^d
Springiness	0.65 ± 0.06^a	0.66 ± 0.02^a	0.66 ± 0.01^a	0.62 ± 0.01^b	0.55 ± 0.01^c
Crispiness	1407.03 ± 47.90^c	2500.93 ± 62.47^b	2672.93 ± 73.94^a	1418.93 ± 32.40^c	233.90 ± 26.55^d
Crunchiness (Nmm)	596.04 ± 25.53^a	325.86 ± 15.64^b	293.31 ± 28.26^c	132.11 ± 17.27^d	32.83 ± 2.63^e
Resilience	0.17 ± 0.03^d	0.52 ± 0.04^b	0.64 ± 0.05^b	0.56 ± 0.05^a	0.27 ± 0.07^c

Note: F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* -flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* -flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour. Data is presented in the form of mean values±standard deviation (n=3). Different superscripts within a row indicate significant differences among samples ($p < 0.05$).

The strength of internal linkages to form a body of food is defined as cohesiveness. Cohesiveness, which has no unit, is also described as the ratio of the area of pressure during the second compression to the area of pressure during the first compression (56). It also represents the ability of food to hold together. F2 showed the highest cohesiveness ($0.70 \pm$

0.03), suggesting an increase in bolus formation that can make it easier during mastication as reported in psyllium and cellulose bread (55). Otherwise, F4 had the less cohesiveness value (0.55 ± 0.04) indicating more brittle or crumblier (57). This result indicated that protein from tilapia flour and dietary fiber from *Ulva lactuca* flour could improve the mastication of wheat-based crackers. The addition of *Ulva lactuca* flour in the tilapia crackers dough increased the amount of water required to achieve the desired crackers dough, indicating an increase the water absorption capacity due to high dietary fiber content in *Ulva lactuca*, i.e. $60.10 \text{ g}/100 \text{ g}$ dry weight (58), which has a strong water-binding capacity. The increase water absorption was originated from ulvan polysaccharides, leading to improve the dough hydration and stability during baking (59). Ulvan, which consists of rhamnose, xylose, glucose, and glucuronic acid, can also modify the viscosity and gel strength of dough due to the hydrophilic nature of sulfated polysaccharides and their ability to form stable networks within the dough matrix, resulting in the improvement of gelatinization and textural properties, such as cohesiveness (60).

Adhesiveness is defined as the negative force area for the first bite, and it shows the work necessary to resist the attraction forces between the surface of a food and the surface of other materials with which the food comes into contact (61). Adhesiveness indicates the ability of food to adhere to the teeth when chewed (62). Wheat-based crackers substituted by tilapia flour showed a similar adhesiveness value with control crackers. However, the addition of *Ulva lactuca* can increase adhesiveness value ($6.92 \pm 0.79 \text{ Nmm}$) in F2, and then this value decreases with an increase in *Ulva lactuca* concentration, i.e. $3.53 \pm 0.03 \text{ Nmm}$ and $1.60 \pm 0.56 \text{ Nmm}$ in F3 and F4, respectively. The higher adhesiveness values indicate the soft texture of food (61).

Springiness or elasticity indicates a rheological characteristic that reflects an object's capacity to recover to its original shape following deformation. In Texture Profile Analysis, the difference between the observed height during the second compression and the original compression distance is used to calculate springiness. It shows the recovery time between the end of the first bite and the beginning of the second bite (61). There are no significant differences between springiness of F0 (0.65 ± 0.06) with F1 (0.66 ± 0.02) and F2 (0.66 ± 0.01), suggesting tilapia flour and low addition of *Ulva lactuca* did not affect the elastic texture of crackers due to the interaction between gluten network and starch gelatinization as previously reported (55). However, the higher addition of *Ulva lactuca* to wheat-based crackers decreases their springiness primarily due to the high water-binding capacity and indigestible nature of ulvan, a key polysaccharide in *Ulva lactuca*. This polysaccharide disrupts the gluten network in the dough, leading to a less elastic and more brittle texture in the final cracker product (25,59). Similar effects are also observed in wheat-based crackers substituted with 10-50% barley, grape seed, olive stone, lupin and chickpea flour (63).

Crispiness is defined as a dry solid food that breaks fast, easily, and completely when bitten with the incisors while making rather loud and high-pitched sounds (64). Crispiness is an important quality that determines the consumer acceptance of crackers. The highest crispiness is found in F2 (2672.93 ± 73.94) and the lowest in F4 (233.90 ± 26.55), indicating tilapia flour and low addition of *Ulva lactuca* increased the crispiness of wheat-based crackers. Meanwhile, crunchiness is defined as a texture of dense foods that cracks when chewed with the molars while creating rather loud and low-pitched sounds (64). Tilapia and *Ulva lactuca* flours decreased the crunchiness of wheat-based crackers, which is probably associated with increasing protein and dietary fiber from tilapia and *Ulva lactuca* flours.

Resilience is the rate of recovery of the sample deformation in terms of speed and strength, on the other hand, it shows the elastic recovery of foods (61). Tilapia and *Ulva lactuca* flours increased the resilience from 0.17 ± 0.03 in F0 to 0.64 ± 0.05 in F2; however, a higher addition of *Ulva lactuca* caused a decrease in the resilience of crackers to 0.27 ± 0.07 in F4. Tilapia flour increases protein and ash content while reducing carbohydrate content thus improve positively structural integrity and resilience of wheat-based crackers. The interaction between polysaccharides and proteins between *Ulva lactuca* and tilapia flour in the dough can lead to the formation of a more stable and cohesive network, improving the overall texture and resilience of the crackers (59). Nevertheless, excessive *Ulva lactuca* can affect the dough's viscoelasticity, leading to decreased cohesiveness and springiness. This results in a less stable dough structure, making the crackers more prone to breaking and less resilience (59). The resilience and cohesiveness of crackers showed a similar pattern as reported in geblek, a cassava-based traditional food from Indonesia that incorporated hydrocolloids (35) and wheat-based crackers substituted with 10-50% barley, grape seed, olive stone, lupin and chickpea flour (63).

3.4. Sensory acceptance of tilapia and *Ulva lactuca* crackers

Sensory acceptance of tilapia and *Ulva lactuca* crackers is presented in Table 5. The sensory characteristics of wheat-based crackers substituted by 25% tilapia flour exhibited a more brownish hue, savory flavor, umami profile, and enhanced crunchiness in comparison to the control group. There were significant differences ($p < 0.05$) in terms of color, flavor, taste, texture, and overall acceptability of F0 and F1 with scores ranging from 3.27 (slightly like) and 3.93 (like), indicating that substitution of 25% tilapia flour in wheat-based crackers could be accepted by panelists. Substitution of 25% tilapia flour increase the savoury and umami that impact on the increasing flavor, taste, texture, and overall acceptability of crackers. The increasing savoury and umami taste of wheat-based crackers substituted 25% tilapia flour is associated with the development of complex and savoury flavors from Maillard Reaction Products (MRPs), such as umami, meaty, roasted, and caramelized, as well as reduce the bitterness (65). However, MRPs and protein crosslinking formed during the reaction can reduce the bioavailability of amino acids and overall protein digestibility (66). The addition of 1-3% *Ulva lactuca* flour in tilapia crackers revealed significant differences compared with control and tilapia crackers (F0 and F1) in color, texture, and overall acceptability, except in flavor and taste, with scores ranging from 2.97 (slightly like) and 4.17 (like). Furthermore, an increased incorporation of *Ulva lactuca* flour diminished the sensory acceptance of crackers, attributed to a more pronounced brown hue, intensified green coloration, and a stronger seaweed flavor. This result indicated that an increase in *Ulva lactuca* flour content had a negative effect on some desirable sensory characteristics in wheat-based crackers. A similar result was reported by Udayangani et al. (40) that the best incorporation of *Ulva lactuca* in nutribars that was acceptable for consumers was 5% than 10% due to stronger green color and seaweed aroma made less consumer acceptance. Meanwhile, Sivaraman et al. (14) showed cookies incorporated with 5% tilapia fish protein concentrate and 2.5-5% *Portieria hornemanii* seaweed were acceptable. Egodavitharana et al. (25) also reported the best crackers incorporated with 4% *Ulva lactuca* powder showed the highest crispiness and acceptance. Biscuit substituted with 5% *Ulva lactuca* powder showed the most well-liked by panelists as reported by Perdani et al (28).

Table 5. Sensory acceptance of tilapia and *Ulva lactuca* crackers.

Parameter	F0	F1	F2	F3	F4
Color	3.67 ± 0.20 ^{bc}	3.87 ± 0.16 ^b	4.17 ± 0.15 ^a	3.67 ± 0.22 ^{bc}	3.20 ± 0.19 ^c
Flavor	3.63 ± 0.41 ^{ab}	3.73 ± 0.23 ^a	3.77 ± 0.17 ^a	2.97 ± 0.29 ^b	3.07 ± 0.14 ^b
Taste	3.50 ± 0.16 ^b	3.77 ± 0.20 ^a	3.73 ± 0.27 ^a	3.17 ± 0.15 ^c	3.20 ± 0.12 ^c
Texture	3.27 ± 0.27 ^d	3.50 ± 0.16 ^b	3.70 ± 0.28 ^a	3.03 ± 0.06 ^e	3.30 ± 0.08 ^c
Overall	3.63 ± 0.16 ^b	3.93 ± 0.23 ^a	3.97 ± 0.11 ^a	3.23 ± 0.03 ^c	3.27 ± 0.03 ^c

Note: 1 = very dislike; 2 = dislike; 3 = slightly like; 4 = like; and 5 = very like. F0 = 100% of wheat flour; F1 = 75% of wheat and 25% tilapia flours; F2 = 75% of wheat and 25% tilapia flours with addition of 1% *Ulva lactuca* -flour; F3 = 75% of wheat and 25% tilapia flours with addition of 2% *Ulva lactuca* -flour; F4 = 75% of wheat and 25% tilapia flours with addition of 3% *Ulva lactuca* flour. Data is presented in the form of mean values ± standard deviation (n=30). Different superscripts within a row indicate significant differences among samples (p < 0.05).

3.5. Principal component analysis of tilapia and *Ulva lactuca* crackers

The Principal Component Analysis (PCA) is used to confirm and illustrate the variables grouping based on the weight of each variable in the variance and covariance matrices. Figure 2a and Figure 2b present the multivariate analysis between cracker formulation, physicochemical properties, texture properties, and sensory acceptance. PCA result indicates the differences between cracker formulations with two principal components depending on the addition of *Ulva lactuca*. The first (PC1) and second (PC2) principal components were 46.74% and 31.55%, respectively, with a total of 78.29% of the variance in the crackers formulation (Figure 2a). The PC1 revealed the combination of a*, b*, C, browning index, hardness, adhesiveness, springiness, crispiness, crunchiness, color, flavor, taste, and overall acceptance with factorial charges > 0.7, and no variables with factorial charges < -0.7. Moreover, the PC2 showed the combination of ash, protein, Fe, ΔE, cohesiveness, and resilience with factorial charges > 0.7, and carbohydrate and L* values with factorial charge < -0.7. The hue value (h) is mostly responsible for separating F4 from other formulations.

Crackers from tilapia flour (F1) and *Ulva lactuca* flour (F2, F3, F4) showed distinct changes in the physicochemical, texture, and sensory acceptance compared to wheat-based crackers (F0) (Figure 2b). Furthermore, a higher addition of *Ulva lactuca* in tilapia crackers significantly increased the ash, protein, and iron content as well as the browning index, cohesiveness, and resilience, however, the sensory acceptability decreased. Both F1 and F2 had a higher lipid and energy content, as well as improved textural qualities such as springiness, crispiness, hardness, adhesiveness, and resilience, as well as increased sensory acceptability (Figure 2b). A similar result is reported in protein enriched biscuits based on oat-milk by-product fortified with chickpea flour (67) and crackers incorporated with *Gracilaria tenuistipitata* (30).

The addition of protein-rich ingredients, such as tilapia flour, can increase the viscoelastic properties by forming additional protein networks that interact with the existing gluten of wheat flour. Protein and polysaccharides of *Ulva lactuca* can interact with proteins of tilapia flour to further enhance the viscoelastic properties. These interactions often involve electrostatic forces and hydrogen bonding, which can lead to a more robust and elastic network. The presence of polysaccharides can also increase the viscosity of the dough, contributing to its overall viscoelastic behaviour. A denser network of protein-polysaccharide interactions leads to increased brittleness. The presence of *Ulva lactuca* polysaccharides, i.e. ulvans which have gelling properties, can contribute to this effect by reinforcing the network. Controlled hydration and gelation of ulvans processes contribute to the brittle texture by forming a solid-like elastic structure. The simultaneous increase in viscoelastic properties and

brittleness in wheat-based crackers with the addition of tilapia and *Ulva lactuca* flour is due to the formation of a dense, robust protein-polysaccharide network that enhances elasticity while also making the structure more rigid and prone to breaking (68,69).

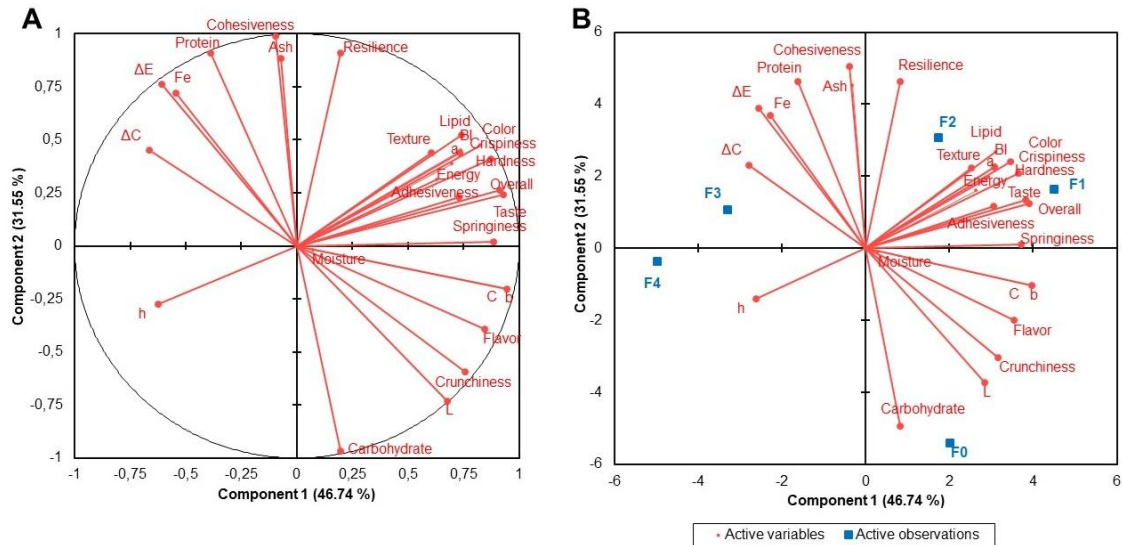


Figure 2. PCA of formulation, physicochemical, texture, and sensory acceptance of tilapia and *Ulva lactuca* crackers (A = projection of variables and B = projection of samples and variables). F0 = 100 % of wheat flour; F1 = 75 % of wheat and 25 % tilapia flours; F2 = 75 % of wheat and 25% tilapia flours with addition of 1 % *Ulva lactuca* -flour; F3 = 75 % of wheat and 25 % tilapia flours with addition of 2% *Ulva lactuca* -flour; F4 = 75% of wheat and 25 % tilapia flours with addition of 3 % *Ulva lactuca* flour.

4. Conclusions

Substitution of tilapia and *Ulva lactuca* flour significantly affected the physicochemical properties, texture, and sensory acceptance of wheat-based crackers. Crackers with substitution of tilapia flour showed higher ash, protein, lipid, Fe, energy, redness (a^*), yellowness (b^*), chroma, browning index, hardness, cohesiveness, springiness, crispiness, and resilience values compared to wheat-based crackers. Tilapia crackers had lower carbohydrate content, lightness, and adhesiveness, but no differences in sensory acceptance between them and wheat-based crackers. Furthermore, addition of *Ulva lactuca* flour in tilapia crackers increased ash, protein, Fe, hue, ΔC , ΔE , cohesiveness, adhesiveness, crispiness, and resilience; however, carbohydrate, lipid content, energy, lightness (L^*), greenness (a^*), yellowness (b^*), chroma, browning index, hardness, and crunchiness values decreased. The higher addition of *Ulva lactuca* flour could decrease the texture properties and sensory acceptance of crackers. Wheat-based crackers substituted by 25% tilapia flour and addition of 1% *Ulva lactuca* flour (F2) were preferred than other formulations. The findings suggest that tilapia and *Ulva lactuca* crackers could provide a nutritious snack with high protein and iron content for mitigate nutritional deficiencies in children and teenagers. Further investigation is needed to study the change in molecular structure, starch digestibility, bioavailability, clinical, and shelf life of crackers to understand their potency and efficacy as a functional food in the food industry and human health.

Acknowledgements

The authors gratefully acknowledge the Universitas Negeri Yogyakarta, Ministry of Education, Culture, Research, and Technology, Republic of Indonesia, for awarding the

prototype research grant (Grants Number: 1.4/UN34/IV/2022). The authors also acknowledge Ms. Aqsha, Ms. Lutfhiyyah, and students who helped for making crackers and sensory analysis.

Author Contributions

NR conceived and designed the experiments; BL and AWP performed the experiments; NR and AWP analyzed the data; NR, BL, AWP wrote the paper.

Funding

The research was funded by Universitas Negeri Yogyakarta, Ministry of Education, Culture, Research, and Technology, Republic of Indonesia, for awarding the prototype research grant (Grants Number: 1.4/UN34/IV/2022).

Institutional Review Board Statement

The ethical clearance of sensory evaluation has been approved by ethics committee of Directorate of Research and Community Service, Universitas Negeri Yogyakarta in accordance to seven standards of WHO 2011, referring to the 2016 CIOMS Guidelines, with description of ethical exemption No. T/3.3/UN34.9/KP.06.07/2022.

Data Availability Statement

Data will be made available on request.

Conflicts of Interest

Authors may declare no conflict of interest.

References

1. Peñarubia O, Toppe J, Ahern M, Ward A, Griffin M. How value addition by utilization of tilapia processing by-products can improve human nutrition and livelihood. *Rev Aquac.* 2023;15(S1):32–40.
2. Food and Agriculture Organization. In Brief to The State of World Fisheries and Aquaculture 2024. Blue Transformation in action. Rome, Italy; 2024.
3. FAO. The state of world fisheries and aquaculture 2022: Towards blue transformation. In Brief to The State of World Fisheries and Aquaculture 2022. Rome, Italy: Food and Agriculture Organization of the United Nations; 2022.
4. Ministry of Marine Affairs and Fisheries Republic of Indonesia. Ministry of Marine Affairs and Fisheries Republic of Indonesia. 2024. Indonesian fisheries production volume data (tonnes).
5. Ministry of Marine Affairs and Fisheries Republic of Indonesia. Data on the production volume of enlargement aquaculture per main commodity (tonnes). 2024.
6. Pangestuti R, Haq M, Rahmadi P, Chun BS. Nutritional value and biofunctionalities of two edible green seaweeds (*Ulva lactuca* and *caulerpa racemosa*) from Indonesia by subcritical water hydrolysis. *Mar Drugs.* 2021;19(10):578.
7. Oliveira LK, Pilz L, Furtado PS, Ballester ELC, Bicudo AJ de A. Growth, nutritional efficiency, and profitability of juvenile GIFT strain of Nile tilapia (*Oreochromis niloticus*) reared in biofloc system on graded feeding rates. *Aquaculture.*

- 2021;541(April):736830.
8. Khanjani MH, Sharifinia M, Hajirezaee S. Recent progress towards the application of biofloc technology for tilapia farming. *Aquaculture*. 2022;552(September 2021):738021.
 9. de Souza MLR, Gasparino E, Goes ES dos R, Coradini MF, Vieira VI, Oliveira GG, et al. Fish carcass flours from different species and their incorporation in tapioca cookies. *Futur Foods*. 2022;5(September 2021):100132.
 10. Justen AP, Souza MLR de, Monteiro ARG, Mikcha JMG, Gasparino E, Delbem ÁB, et al. Preparation of Extruded Snacks with Flavored Flour Obtained from the Carcasses of Nile Tilapia: Physicochemical, Sensory, and Microbiological Analysis. *J Aquat Food Prod Technol*. 2017;26(3):258–66.
 11. Monteiro MLG, Mársico ET, Soares MS, Deliza R, de Oliveira DCR, Conte-Junior CA. Tilapia-waste flour as a natural nutritional replacer for bread: A consumer perspective. *PLoS One*. 2018;13(5):e0196665.
 12. Monteiro MLG, Mársico ET, Deliza R, Castro VS, Mutz YS, Soares Junior MS, et al. Physicochemical and sensory characteristics of pasta enriched with fish (*Oreochromis niloticus*) waste flour. *Lwt*. 2019;111(May):751–8.
 13. Zulaikha Y, Yao SH, Chang YW. Physicochemical and functional properties of snack bars enriched with tilapia (*Oreochromis niloticus*) by-product powders. *Foods*. 2021;10:1908.
 14. Sivaraman L, Deshmukhe G, Xavier KAM, Hirekudel SK, Desai AS, Balange AK. Effect of incorporation of seaweed (*Portieria hornemanii*) and Tilapia fish protein concentrate on the nutritional, physical and sensory attributes of cookies. *Int J Food Sci Technol*. 2023;58(8):4415–24.
 15. Kasyani K, Mursyid M, Perdana SM, Ibnu IN, Lanita U, Wazzan H. Biscuit Formulation Substitutes Wheat Flour with Tempeh Flour and Nile Tilapia Fish Flour as Complementary Food to Prevent Stunting. *Indones Food Sci Technol J*. 2025;8(2):245–52.
 16. Maisont S, Samutsri W, Phae-ngam W, Limsuwan P. Development and Characterization of Crackers Substitution of Wheat Flour With Jellyfish. *Front Nutr*. 2021;8(December):1–9.
 17. Xu J, Zhang Y, Wang W, Li Y. Advanced properties of gluten-free cookies, cakes, and crackers: A review. *Trends Food Sci Technol*. 2020;103(April):200–13.
 18. Mondelez International. The Fourth Annual State of Snacking. 2022.
 19. Andarwulan N, Madanijah S, Briawan D, Anwar K, Bararah A, Saraswati, et al. Food consumption pattern and the intake of sugar, salt, and fat in the South Jakarta City—Indonesia. *Nutrients*. 2021;13(4):1–19.
 20. World Health Organization. Nutritional anaemias : Tools for effective prevention and control. World Health Organization. Geneva: World Health Organization; 2017. 1–83 p.
 21. Institute of Medicine. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. 2001.
 22. Benjakul S, Karnjanapratum S. Characteristics and nutritional value of whole wheat cracker fortified with tuna bone bio-calcium powder. *Food Chem*. 2018;259(November

- 2017):181–7.
23. Batista AP, Niccolai A, Bursic I, Sousa I, Raymundo A, Rodolfi L, et al. Microalgae as functional ingredients in savory food products: Application to wheat crackers. *Foods*. 2019;8(12):611.
 24. Idowu AT, Benjakul S, Sinthusamran S, Pongsetkul J, Sae-Leaw T, Sookchoo P. Whole wheat cracker fortified with bio-calcium and protein hydrolysate powders from salmon frame: Characteristics and nutritional value. *Food Qual Saf*. 2019;3(3):191–9.
 25. Egodavitharana DI, Manori Bambaranda BVAS, Mudannayake DC. Phytochemical Composition of Two Green Seaweeds (*Ulva lactuca* and *Ulva fasciata*) and their Utilization as a Functional Ingredient in Crackers. *J Aquat Food Prod Technol*. 2023;32(2):158–74.
 26. Ayudiarti DL, Adhiyyah I, Suryanti, Syamdidi, Hastarini E, Suryaningrum TD, et al. Characteristic of fortified crackers with largehead hairtail (*trichiurus lepturus*) fish flour. *IOP Conf Ser Earth Environ Sci*. 2021;860:012076.
 27. Aganduk AA, Matanjun P, Tan TS, Khor BH. Proximate and physical analyses of crackers incorporated with red seaweed, *Kappaphycus alvarezii*. *J Appl Phycol*. 2023;36(2):867–73.
 28. Perdani AW, Ratnaningsih N, Chayati I, Utami NN. Nutritional, physicochemical and sensory evaluation of biscuits enriched with *Ulva* sp. from Gunungkidul coast. *Food Res*. 2024;8(Supplementary 2):22–9.
 29. Simaremare P, Ratnaningsih N, Lastariwati B. Karakteristik Crackers Hasil Fortifikasi Tepung Ikan Teri (*Stolephorus* sp.) dan Rumput Laut (*Ulva lactuca*) untuk Anak Usia Sekolah. *J Pascapanen dan Bioteknologi Kelaut dan Perikanan*. 2024;19(1):1–16.
 30. Raiyan A, Hossain M, Zahid A, Lina NN, Shuvo S Das, Parvin R. Physicochemical characterization and microbial quality evaluation of *Gracilaria tenuistipitata* added crackers. *Appl Food Res*. 2024;4(2):100623.
 31. AOAC. AOAC: Official Methods of Analysis (Volume 1). Vol. 1. 2005.
 32. Sudiarta W, Ratnayani O, Kadek Veliyana A. Analisis Kadar Logam Besi dalam Susu Bubuk Formula Kehamilan Secara Spektrofotometri Serapan Atom. *J Media Sains-Maret*. 2019;3(1):1–6.
 33. Ratnaningsih N, Suparmo, Harmayani E, Marsono Y. Physicochemical properties, in vitro starch digestibility, and estimated glycemic index of resistant starch from cowpea (*Vigna unguiculata*) starch by autoclaving-cooling cycles. *Int J Biol Macromol*. 2020;142:191–200.
 34. Cefola M, D'Antuono I, Pace B, Calabrese N, Carito A, Linsalata V, et al. Biochemical relationships and browning index for assessing the storage suitability of artichoke genotypes. *Food Res Int*. 2012;48(2):397–403.
 35. Ratnaningsih N, Sugati D, Handayani THW, Handayani S, Devi MK. Effect of addition of texturizer on the proximate content and texture properties of geblek, a cassava starch-based traditional food from Indonesia. *Food Res*. 2023;7:208–16.
 36. Indonesian National Standard. SNI Biskuit 2973:2022. Indonesia; 2022.
 37. Nammakuna N, Barringer SA, Ratanatriwong P. The effects of protein isolates and hydrocolloids complexes on dough rheology, physicochemical properties and qualities of gluten-free crackers. *Food Sci Nutr*. 2016;4(2):143–55.
 38. Kumar A, Krishnamoorthy E, Devi HM, Uchoi D, Tejpal CS, Ninan G, et al. Influence of sea grapes (*Caulerpa racemosa*) supplementation on physical, functional, and anti-

- oxidant properties of semi-sweet biscuits. *J Appl Phycol*. 2018;30(2):1393–403.
39. Bajad RB, Kamble MG, Gawai SR, Syed I, Roy M. Analysis of physicochemical , functional , and antioxidant properties of four different Indian seaweed species. *Futur Foods*. 2024;10(August):100435.
 40. Udayangani C, Wijesekara I, Wickramasinghe I. Characterization of sea lettuce (*Ulva lactuca*) from Matara, Sri Lanka and development of nutribars as a functional food. *Ruhuna J Sci*. 2019;10(2):96–107.
 41. Mohan HE, Madhusudan S, Baskaran R. The sea lettuce *Ulva sensu lato*: Future food with health-promoting bioactives. *Algal Res*. 2023;71(June 2022):103069.
 42. Xu J, Liao W, Liu Y, Guo Y, Jiang S, Zhao C. An overview on the nutritional and bioactive components of green seaweeds. *Food Prod Process Nutr*. 2023;5(1):18.
 43. Monteiro MLG, Mársico ET, Soares MS, Magalhães AO, Canto ACVCS, Costa-Lima BRC, et al. Nutritional profile and chemical stability of pasta fortified with tilapia (*Oreochromis niloticus*) flour. *PLoS One*. 2016;11(12):e0168270.
 44. Rasyid A. Evaluation of nutritional composition of the dried seaweed *Ulva lactuca* from Pameungpeuk waters, Indonesia. *Trop Life Sci Res*. 2017;28(2):119–25.
 45. Bakare AH, Adeola AA, Otesile I, Obadina AO, Afolabi WA, Adegunwa MO, et al. Nutritional, Texture, and Sensory Properties of composite biscuits produced from breadfruit and wheat flours enriched with edible fish meal. *Food Sci Nutr*. 2020;8(11):6226–46.
 46. 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(2):949–82.
 47. Palacio MI, Etcheverría AI, Manrique GD. Development of gluten-free muffins utilizing squash seed dietary fiber. *J Food Sci Technol*. 2018;55(8):2955–62.
 48. Devu SS, Dileepmon R, Kothakota A, Venkatesh T, Pandiselvam R, Garg R, et al. Recent advancements in baking technologies to mitigate formation of toxic compounds: A comprehensive review. *Food Control*. 2022;135(January):108707.
 49. Al-Asmar A, Giosafatto CVL, Sabbah M, Mariniello L. Hydrocolloid-based coatings with nanoparticles and transglutaminase crosslinker as innovative strategy to produce healthier fried kobbah. *Foods*. 2020;9(6):698.
 50. Verma V, Yadav N. Acrylamide content in starch based commercial foods by using high performance liquid chromatography and its association with browning index. *Curr Res Food Sci*. 2022;5(February):464–70.
 51. Zhang N, Zhou Q, Fan D, Xiao J, Zhao Y, Cheng KW, et al. Novel roles of hydrocolloids in foods: Inhibition of toxic maillard reaction products formation and attenuation of their harmful effects. *Trends Food Sci Technol*. 2021;111(October 2020):706–15.
 52. Nishinari K, Peyron MA, Yang N, Gao Z, Zhang K, Fang Y, et al. The role of texture in the palatability and food oral processing. *Food Hydrocoll [Internet]*. 2024;147:109095. Available from: <https://www.sciencedirect.com/science/article/pii/S0268005X23006410>
 53. Texture Technologies Corp. Texture Technologies. 2021. Overview of Texture Profile Analysis (TPA).
 54. Nicole TZH, Nichelle TS, Elizabeth TE, Yuliarti O. Formulation of functional crackers enriched with fermented soybean (tempeh) paste: rheological and microstructural properties. *Futur Foods*. 2021;4(December 2020):100050.

55. Bilgic H, Sensoy I. Effect of psyllium and cellulose fiber addition on the structure and the starch digestibility of bread and crackers. *Food Struct.* 2023;35(November 2022):100302.
56. Bland JM, Bett-Garber KL, Li CH, Brashear SS, Lea JM, Bechtel PJ. Comparison of sensory and instrumental methods for the analysis of texture of cooked individually quick frozen and fresh-frozen catfish fillets. *Food Sci Nutr.* 2018;6(6):1692–705.
57. Boz H. Effect of flour and sugar particle size on the properties of cookie dough and cookie. *Czech J Food Sci.* 2019;37(2):120–7.
58. Mohan EH, Madhusudan S, Rao JNS, Monika PR, Prabhasankar P, Baskaran R. Structural , quality , and shelf-life assessment of pasta enriched with seaweed *Ulva lactuca*. *Food Biosci.* 2025;68(April):106390.
59. Wang Z, Wang L, Yu X, Wang X, Zheng Y, Hu X, et al. Effect of polysaccharide addition on food physical properties : A review. *Food Chem.* 2024;431(August 2023).
60. Ma M, Gu Z, Cheng L, Li Z, Li C. Effect of hydrocolloids on starch digestion : A review. *Food Chem.* 2024;444(February):138636.
61. Chandra M V., Shamasundar BA. Texture profile analysis and functional properties of gelatin from the skin of three species of fresh water fish. *Int J Food Prop.* 2015;18(3):572–84.
62. Paula AM, Conti-Silva AC. Texture profile and correlation between sensory and instrumental analyses on extruded snacks. *J Food Eng.* 2014;121(1):9–14.
63. Giannoutsos K, Panagiotis A, Ioanna D, Menexes G, Mourtzinos I, Sarris D, et al. Production of functional crackers based on non-conventional flours . Study of the physicochemical and sensory properties. *Food Chem Adv.* 2023;2(December 2022):100194.
64. Tunick MH, Onwulata CI, Thomas AE, Phillips JG, Mukhopadhyay S, Sheen S, et al. Critical evaluation of crispy and crunchy textures: A review. *Int J Food Prop.* 2013;16(5):949–63.
65. Hao J, Zhang X, Wang Z, Zhao Q, Zhang S, Li Y. Maillard reaction products of soybean protein hydrolysates and reducing sugar : Structure and flavor insights. *Food Res Int.* 2025;202:115790.
66. Ding W, Bai Y. Influence of Nonenzymatic Browning Reactions on the Digestibility and Gut Microbiota Fermentation of Starch and Protein. *Compr Rev Food Sci Food Saf.* 2025;24:e70299.
67. Wang A, Zhu Y, Zou L, Zhao G, Wu J. Development of protein-enriched biscuit based on oat-milk byproduct fortified with chickpea flour. *Lwt.* 2023;177(November 2022):114594.
68. Collar C. Structuring Diluted Wheat Matrices : Impact of Heat-Moisture Treatment on Protein Aggregation and Viscoelasticity of Hydrated Composite Flours. *Food Bioprocess Technol.* 2020;02406-z.
69. Alfaris NA, Gupta AK, Khan D, Khan M, Aldayel TS. Impacts of wheat bran on the structure of the gluten network as studied through the production of dough and factors affecting gluten network. *Food Sci Technol.* 2022;42:e37021.