



Nutritional, Physicochemical and Sensory Evaluation of Geblek, a Traditional Food from Kulon Progo Regency Enriched with *Ulva* sp. from Gunungkidul Coast

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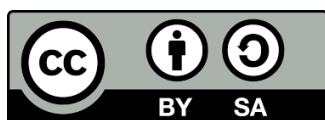
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Abstract

Geblek is a traditional cassava-based snack from Kulon Progo, Yogyakarta, that generally has limited nutritional value because of its relatively simple ingredient composition. *Ulva* sp., a green seaweed, contains macro- and micronutrients, antioxidants, and other bioactive compounds, making it a potential functional food ingredient. This study aimed to evaluate the effects of *Ulva* sp. supplementation on the nutritional composition, physicochemical properties, and sensory characteristics of geblek. *Ulva* sp. was obtained from seaweed farmers in Gunungkidul, dried, processed into powder, and incorporated into geblek at concentrations of 0% (STD), 2% (GU2), 4% (GU4), and 6% (GU6). Proximate composition, antioxidant activity (IC₅₀), crude fiber content, color parameters (L*, a*, and b*), texture, and sensory characteristics were evaluated. The results showed that *Ulva* sp. supplementation increased fat and ash contents, reduced moisture content, and did not significantly affect carbohydrate or protein contents. Antioxidant activity improved significantly ($p < 0.05$), whereas crude fiber content remained unchanged. Texture measurements were significantly higher in geblek supplemented with 4% *Ulva* sp. (13.63 ± 1.85 N) than in the control (9.17 ± 1.07 N). The color values of the supplemented samples decreased because of the green pigmentation of *Ulva* sp. powder. Sensory evaluation indicated that the appearance, taste, and overall acceptability of geblek supplemented with 4% *Ulva* sp. were comparable to those of the control, whereas supplementation at 6% reduced sensory preference. No significant differences in aroma or texture attributes were observed among the treatments. In conclusion, supplementation with *Ulva* sp. improved selected nutritional and physicochemical characteristics of geblek while maintaining sensory acceptability at moderate supplementation levels.



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INTRODUCTION

The development of traditional foods plays a crucial role in safeguarding cultural heritage while ensuring their continued relevance in contemporary society (Banda et al., 2024; Chukwurah et al., 2025; Ghosh et al., 2023; Pugra et al., 2025; Singh, 2026). Several factors underscore the importance of this effort, including the preservation of regional culture and identity, enhancement of economic value and competitiveness, adaptation to evolving consumer preferences, product diversification through flavor innovation, and application of modern technologies in production and marketing. Traditional foods represent an integral component of cultural heritage that embodies local history and indigenous knowledge. Through appropriate innovation and modernization, these foods can remain attractive to younger generations, thereby contributing to the preservation of culinary traditions. Furthermore, transforming traditional foods into value-added products has the potential to strengthen

culinary tourism and support the development of local micro, small, and medium enterprises (MSMEs). In response to increasing consumer demand for nutritious, convenient, and health-oriented food products, appropriate recipe modifications, such as reducing oil or sugar content, may improve the nutritional profile and market relevance of traditional foods. Additionally, diversification of flavors and product forms may further enhance consumer interest and acceptance. Thus, the strategic development of traditional foods can contribute to cultural preservation, economic sustainability, and the availability of more nutritious food options (Aprina et al., 2024).

Geblek is a traditional culinary product originating from Kulon Progo Regency, Special Region of Yogyakarta, Indonesia. It is prepared from cassava (*Manihot esculenta*) and tapioca starch, seasoned with garlic (*Allium sativum*) and salt, and subsequently deep-fried. The product is characterized by a chewy interior, a slightly crisp exterior, and a distinctive savory flavor. The development of geblek is closely associated with cassava cultivation in Kulon Progo, where cassava serves as an important local agricultural commodity and raw material for tapioca production. As part of the region's gastronomic heritage, geblek is widely available in traditional markets and from street vendors and is commonly consumed with tempeh bengkak bacem or chili-based condiments, reinforcing its status as a culturally significant local food (Ismiana et al., 2023).

Nutritionally, geblek is predominantly a carbohydrate-rich food because of its cassava and tapioca base, while its protein and dietary fiber contents are relatively low. Its fat content is influenced by the frying process and the characteristics of the cooking oil used. Despite these nutritional limitations, geblek has considerable cultural, economic, and product-development potential. Innovations involving flavor diversification, modern packaging, and digital marketing may enhance its competitiveness in the contemporary food market (A'yuni & Santoso, 2018).

Sea lettuce (*Ulva* sp.) is a nutrient-rich marine green alga containing macro- and micronutrients, antioxidants, and various bioactive compounds, making it a potentially valuable ingredient for food and pharmaceutical applications (Kidgell et al., 2019). The genus *Ulva* occurs along Indonesian coastlines and is characterized by rapid growth, adaptability to diverse environmental conditions, and a biochemical composition of considerable biotechnological interest. Among its bioactive constituents, ulvan, a sulfated polysaccharide, has attracted particular attention because of its reported antioxidant, anti-inflammatory, and immunomodulatory properties (Febrianto et al., 2019).

The nutritional composition of *Ulva* spp. may include substantial amounts of protein and carbohydrates, including water-soluble polysaccharides such as ulvan, while its lipid content is generally relatively low. Its lipid fraction contains polyunsaturated fatty acids, and *Ulva* also contains various vitamins, minerals, chlorophylls, and carotenoids that contribute to its potential as a functional food ingredient (Kidgell et al., 2019). Previous studies have incorporated *Ulva* sp. into biscuit formulations and reported changes in nutritional and physicochemical characteristics while maintaining acceptable sensory properties (Perdani et al., 2024).

Nutritionally, the relatively high carbohydrate content and comparatively low protein and dietary fiber contents of geblek provide opportunities for formulation with nutrient-rich ingredients. Incorporating seaweed into this traditional product may therefore offer an

approach to improving selected nutritional and functional characteristics while maintaining its cultural identity. However, such modifications must also consider physicochemical properties and sensory acceptance because changes in formulation may affect the color, texture, aroma, taste, and overall acceptability of the final product (A'yuni & Santoso, 2018).

Although the incorporation of *Ulva* sp. into bakery products has previously been investigated (Perdani et al., 2024), research on the supplementation of *geblek* with seaweed-based ingredients remains limited. The incorporation of *Ulva* sp. powder into *geblek* may modify its nutritional composition, particularly its mineral and antioxidant contents, as well as its physicochemical and sensory characteristics. Accordingly, further investigation is required to determine whether *Ulva* sp. can be incorporated at appropriate concentrations while maintaining acceptable product characteristics.

This study therefore aims to investigate the nutritional composition, physicochemical properties, and sensory characteristics of *geblek* supplemented with *Ulva* sp. powder. The broader objective is to promote the utilization of locally available seaweed from Gunungkidul while supporting the development of *geblek* as a traditional food with enhanced functional potential. The theoretical contribution of this research is to extend the literature on the incorporation of seaweed-based ingredients into traditional foods, particularly within the context of Indonesian culinary heritage. Its practical contribution is to provide evidence that may support local food producers and MSMEs in developing value-added traditional food products that retain their cultural significance. The contribution of this research further lies in integrating nutritional, physicochemical, and sensory evaluations to assess the effects of *Ulva* sp. supplementation on *geblek* and explore its potential as a locally available ingredient for the development of traditional food products with improved nutritional and functional characteristics.

METHOD

Materials

Ulva sp. was sourced from seaweed farmers located along the coastal area of Gunungkidul, Yogyakarta, Indonesia. Cassava (*Manihot esculenta*) and additional ingredients required for *geblek* preparation were procured from a local market in Wonosari, Gunungkidul Regency.

Ulva sp. powder production

Ulva sp. was thoroughly washed with clean water to remove impurities and subsequently dried. The dried material was then milled into powder and passed through an 80-mesh sieve to obtain a uniform particle size.

Geblek production

The formulation and ingredient composition of *geblek* enriched with *Ulva* sp. flour at 0% (STD), 2% (GU2), 4% (GU4), and 6% (GU6) substitution levels are presented in Table 1. The dough was prepared by thoroughly mixing cassava, tapioca flour, *Ulva* sp. flour, garlic, and salt until homogeneous. The mixture was then steamed at 100 °C for 15 minutes. After steaming, the dough was kneaded and manually shaped into ring like forms resembling the letter “O.” The shaped dough pieces were fried in refined cooking oil at 170–180 °C for approximately 3–5 minutes until a golden-brown color was achieved. Following frying, the *geblek* samples were drained on absorbent paper to reduce residual oil content.

Table 1. Recipe of *geblek* enriched with *Ulva* sp.

Ingredients	STD (g)	GU2 (g)	GU4 (g)	GU6 (g)
<i>Ulva</i> sp. powder	0	2	4	6
Grated cassava	100	100	100	100
Stock powder	3	3	3	3
Salt	1	1	1	1
Water	16	16	16	16

Nutritional value

The nutritional parameters analyzed included protein, fat, carbohydrate, moisture, and ash contents, following the procedures outlined by AOAC (2002). Fat content was determined using the Soxhlet extraction method (Weibull procedure). Protein content was quantified using the Kjeldahl method with a Kjeltex protein analyzer (Foss Tecator AB, Sweden). Carbohydrate content was calculated by difference, while moisture and ash contents were determined by the gravimetric method.

Determination of antioxidant activity using DPPH

Antioxidant activity of *geblek* was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) method, following the procedure of Ningrum et al. (2021) with slight modifications. The *geblek* samples were ground and extracted with 99% methanol under stirring for 5 min. The extract was then centrifuged at 2,700 rpm for 10 min at room temperature. A 1.5 mL aliquot of the resulting supernatant was mixed with 1.5 mL of 0.1 mM DPPH solution and incubated in the dark at room temperature for 30 min. Absorbance was measured at 517 nm using a UV–Vis spectrophotometer.

The radical scavenging activity (RSA) was calculated using Equation (1):

$$(1) \quad \%RSA = \left(1 - \frac{A_{sample}}{A_{blank}} \right) \times 100$$

The percentage of RSA was plotted against sample concentration to determine the half-maximal inhibitory concentration (IC₅₀). Linear interpolation was applied if the response curve was linear, while curve fitting was used for non linear regions. The IC₅₀ values were expressed in µg/mL (ppm), according to the concentration units used.

Determination of crude fiber

Crude fiber content of *geblek* samples was determined using the AOAC (2025) proximate method. Approximately 2 g of ground dry sample was weighed into an Erlenmeyer flask, followed by the addition of 200 mL of 0.255 N sulfuric acid (H₂SO₄). The mixture was refluxed for 30 min while maintaining a constant volume. The residue was then filtered through ash-free filter paper and washed with hot distilled water until neutral. Subsequently, the residue was refluxed with 200 mL of 0.313 N sodium hydroxide (NaOH) for 30 min, filtered, and washed again with hot distilled water, followed by sequential washing with 96% ethanol and petroleum ether. The filter paper containing the residue was dried in an oven at 105 °C to constant weight, cooled in a desiccator, and weighed to obtain the initial residue weight (W1). The dried residue was then incinerated in a muffle furnace at 550 °C for approximately 3 h, cooled in a desiccator, and weighed again to obtain the ash weight (W2). Crude fiber content was calculated as the difference between W1 and W2, relative to the initial sample weight, and

expressed as a percentage (%).

Texture

The texture of *geblek* samples was evaluated using a Universal Testing Machine (UTM) texture analyzer following the compression test method described by Bourne (2002). Samples were prepared with dimensions of approximately 1.5 cm in thickness and 3 cm in diameter. Each sample was placed on the UTM platform and compressed perpendicularly to the surface using a cylindrical probe (36 mm diameter). The test was performed at a crosshead speed of 50 mm/min until maximum deformation or sample breakage occurred. Force (N) and displacement (mm) data were automatically recorded by the instrument software and subsequently analyzed to determine texture parameters, with hardness as the primary variable. Measurements were conducted in duplicate, and results are expressed as mean $\pm$ standard deviation.

Color

The color of *geblek* samples was measured using a Chromameter (Model CR-400, Konica Minolta, Osaka, Japan) following the method of Ningrum et al. (2021) with minor modifications. The instrument was calibrated prior to measurement using a standard white calibration plate. Color parameters were recorded in the CIE Lab* system, where L* represents lightness, a* indicates the red–green coordinate, and b* indicates the yellow–blue coordinate. Measurements were performed in duplicate, and mean values were reported.

Organoleptic test for sensory evaluation

Sensory evaluation of *geblek* was conducted using a hedonic test with 20 semi-trained panelists, following the method of Noviatry et al. (2020) with modifications. Panelists evaluated five attributes: color, taste, aroma, texture, and overall acceptability. Samples consisted of *geblek* enriched with *Ulva* sp. flour at four levels (STD, GU2, GU4, and GU6). Each panelist was provided with all samples at individual desks, along with bottled mineral water for palate cleansing and a digital questionnaire accessed via Google Forms. A five-point facial hedonic scale was employed (1 = dislike extremely, 5 = like extremely), and panelists recorded their responses accordingly.

Statistical Analysis

All experiments were performed in duplicate, and results were expressed as mean $\pm$ standard deviation (SD). A completely randomized design was applied. Data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics software (Version 20.0; IBM Corp., Armonk, NY, USA). Mean comparisons were conducted using Duncan's multiple range test at a 5% significance level. Differences were considered statistically

RESULTS AND DISCUSSION

Nutritional value

The proximate composition of *geblek*, including protein, fat, carbohydrate, moisture, and ash contents, is presented in Table 2. Enrichment with *Ulva* sp. flour resulted in a significant increase ($p < 0.05$) in fat and ash contents, accompanied by a significant decrease ($p < 0.05$) in moisture content. In contrast, protein and carbohydrate contents did not differ significantly among treatments.

Table 2. Nutritional value of *geblek* enriched with *Ulva* sp.

<i>Geblek</i>	Protein (%)	Fat (%)	Carbohydrate (%)	Moisture (%)	Ash (%)
STD	1.13±0.12 ^a	3.38±0.09 ^a	38.18±0.22 ^{ab}	50.83±0.00 ^a	1.35±0.02 ^a
GU2	1.24±0.00 ^a	5.27±0.09 ^c	35.89±1.23 ^a	50.27±0.01 ^a	1.65±0.04 ^{ab}
GU4	1.21±0.03 ^a	4.46±0.06 ^b	39.69±0.11 ^b	48.28±0.13 ^b	2.44±0.24 ^{bc}
GU6	1.33±0.00 ^a	5.64±0.20 ^c	40.08±1.16 ^b	46.40±0.08 ^c	2.99±0.48 ^c

Values are presented as mean±SD. Values with different superscripts within the same columns are statistically significantly different ($p < 0.05$).

As shown in Table 2, protein content did not differ significantly among treatments. However, the highest mean protein level was observed in the 6% *Ulva* sp. supplementation group (GU6). Previous studies have reported relatively high protein levels in *Ulva lactuca*, approximately 17.38% (Putra et al., 2024). The absence of significant differences in this study may be attributed to the relatively small proportion of *Ulva* sp. flour used in the formulations, which limited its contribution to the overall protein content of *geblek*.

Fat content exhibited an increasing trend with higher levels of *Ulva* sp. incorporation, with the maximum value observed in the GU6 treatment. Although the intrinsic lipid content of *Ulva* sp. is relatively low (da Costa et al., 2018), the presence of non-polar constituents in the seaweed may promote greater oil absorption during frying, thereby contributing to the elevated fat levels in the fortified *geblek* samples.

Carbohydrate content in *geblek* enriched with *Ulva* sp. was marginally higher than that of the control (STD), particularly in the GU4 and GU6 treatments. Green seaweeds such as *Ulva lactuca* typically contain ~20.4% carbohydrate (Rusli et al., 2023). However, given the relatively low inclusion levels of *Ulva* sp. flour, only minor variations in carbohydrate content were detected among treatments.

Moisture content decreased progressively with increasing levels of *Ulva* sp. addition. This reduction may be attributable to the presence of non-polar compounds in *Ulva* sp., which can decrease the water-binding capacity of the food matrix, thereby lowering moisture retention.

Ash content increased proportionally with the concentration of *Ulva* sp., reflecting an enhancement in mineral content. This observation aligns with the high mineral composition of *Ulva lactuca*, which has been reported to exceed that of many other seaweed species (Rusli et al., 2023).

Antioxidant Activity

The antioxidant activity of *geblek* enriched with *Ulva* sp. was evaluated using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The results, expressed as IC₅₀ values, are presented in Figure 1. According to Molyneux (2004), lower IC₅₀ values indicate higher antioxidant activity, as a smaller concentration of the sample is required to inhibit 50% of DPPH radicals. Thus, a decrease in IC₅₀ corresponds to an enhancement in antioxidant capacity.

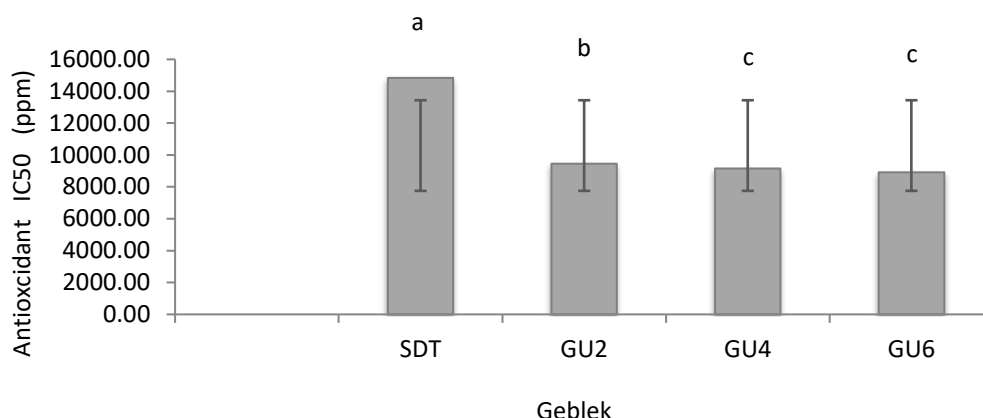


Figure 1. Antioxidant IC₅₀ of *Geblek* enriched with *Ulva* sp. Bars with different notations are statistically significantly different ($p < 0.05$).

Figure 1 demonstrates that IC₅₀ values differed significantly among treatments. The GU2, GU4, and GU6 formulations exhibited lower IC₅₀ values than the control (STD), indicating higher antioxidant activity. A progressive reduction in IC₅₀ was observed with increasing levels of *Ulva* sp. incorporation, confirming a dose-dependent enhancement of antioxidant capacity. The elevated activity may be attributed to the bioactive compounds present in *Ulva* species. *Ulva lactuca*, for example, has been reported to contain chlorophylls (a, b, and c) as well as carotenoids such as neoxanthin, antheraxanthin, dinoxanthin, flavoxanthin, micronone, and vaucheriaxanthin, along with other unidentified pigments, all of which exhibit potential antioxidant properties (da Costa et al., 2018).

Crude fiber

The crude fiber content of *geblek* enriched with *Ulva* sp. is presented in Figure 2. No significant differences were observed among treatments. Previous studies have reported that *Ulva* sp. contains approximately 3.68% crude fiber (Jatmiko et al., 2019). Given this relatively low fiber content, the incorporation of *Ulva* sp. flour at the tested levels did not exert a measurable effect on the crude fiber content of the fortified *geblek* samples.

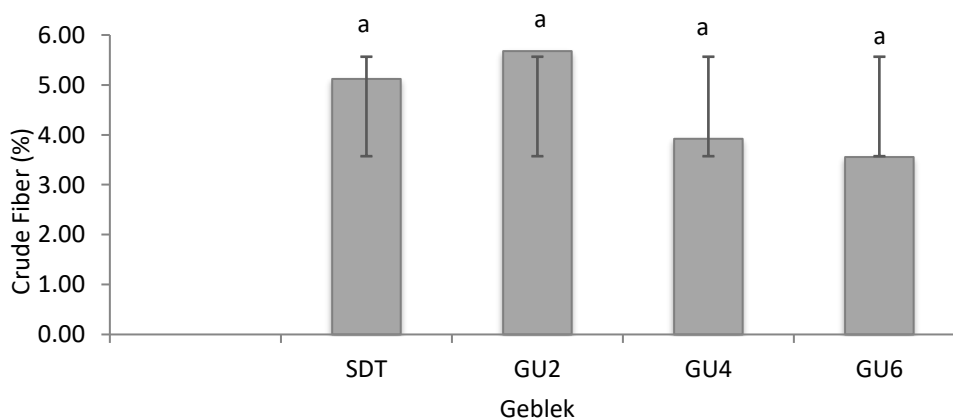


Figure 2. Crude fiber of *geblek* enriched with *Ulva* sp. Bars with different notations are statistically significantly different ($p < 0.05$).

Dietary fiber plays an important role in human health, with high fiber foods contributing to weight management and improved digestive function. Coarse fiber facilitates gastrointestinal transit by accelerating the elimination of food residues (Soeprijadi et al., 2023). Moreover, regular consumption of fiber rich foods has been associated with a reduced risk of chronic diseases, including diabetes, obesity, hypertension, cardiovascular disease, and certain cancers (Kumar et al., 2018).

Texture

Food quality is strongly influenced by sensory attributes, including texture. The texture values of *geblek* enriched with *Ulva* sp. are presented in Table 2. Among the four treatments, GU4 exhibited the highest texture value (13.63 ± 1.85 N), which was significantly different from the other treatments. In contrast, GU2 and GU6 did not differ significantly from the control (STD). In this study, texture was expressed as the force required to fracture the *geblek*.

Table 3. Texture value of *geblek* enriched with *Ulva* sp.

<i>Geblek</i>	Texture (N)
STD	9.17 ± 1.07^a
GU2	8.24 ± 0.89^a
GU4	13.63 ± 1.85^b
GU6	10.17 ± 0.34^a

Values are presented as mean $\pm$ SD. Values with different superscripts within the same columns are statistically significantly different ($p < 0.05$).

The texture measurements indicated no substantial differences between *geblek* enriched with *Ulva* sp. and the control, suggesting that *Ulva* sp. incorporation did not negatively affect texture quality. This finding is consistent with previous reports that seaweed components can contribute to improved texture and overall product quality (Salehi, 2019).

Color and appearance

Color is a critical quality parameter influencing consumer preference. The color attributes (L^* , a^* , b^*) of *geblek* enriched with *Ulva* sp. are presented in Table 4. Increasing *Ulva* sp. concentration significantly decreased the L^* value ($p < 0.05$), indicating a darker product. The a^* values of enriched samples were lower than the control, reflecting a shift toward greenness due to the natural pigmentation of *Ulva* sp. powder. Similarly, the b^* values decreased, suggesting reduced yellowness in the fortified samples.

Table 4. Color of *geblek* enriched with *Ulva* sp.

<i>Geblek</i>	L	a^*	b^*
STD	52.31 ± 0.23^a	-2.81 ± 0.09^a	11.39 ± 0.06^a
GU2	51.21 ± 0.23^b	-2.27 ± 0.01^b	9.38 ± 0.13^b
GU4	45.57 ± 0.09^c	-2.13 ± 0.03^b	9.09 ± 0.03^b
GU6	39.26 ± 0.04^d	-1.77 ± 0.02^c	8.18 ± 0.19^c

Values are presented as mean $\pm$ SD. Values with different superscripts within the same columns are statistically significantly different ($p < 0.05$).



Figure 3. Appearance of *geblek* enriched with *Ulva* sp.

The incorporation of *Ulva* sp. contributed to the dark greenish appearance of *geblek*, as shown in Figure 3. *Ulva* sp., a green seaweed (Chlorophyta), contains chlorophyll as the dominant pigment, which is responsible for the observed green coloration (Bayomi, 2022). Similar findings have been reported in bakery products, where *Ulva* sp. supplementation imparted a greenish hue to biscuits (Perdani et al., 2024).

Sensory evaluation

The sensory evaluation results for *geblek* enriched with *Ulva* sp. are presented in Table 5. The attributes assessed included appearance, aroma, texture, taste, and overall acceptability. Appearance scores decreased with increasing *Ulva* sp. concentrations, with GU6 (2.8 ± 1.11) rated significantly lower than the control (STD, 3.75 ± 0.64). No significant differences were observed for aroma and texture, as all treatments received comparable scores. However, higher concentrations of *Ulva* sp. negatively affected taste and overall acceptability. At lower concentrations, such as GU2, consumer ratings for taste remained comparable to the control.

Table 5. Organoleptic test of *geblek* enriched with *Ulva* sp.

<i>Geblek</i>	Appearance	Aroma	Texture	Taste	Overall
STD	3.75 ± 0.64^a	3.6 ± 0.99^a	2.55 ± 0.60^a	3.35 ± 0.99^a	3.35 ± 0.75^a
GU2	3.1 ± 0.85^b	3.55 ± 0.69^a	3.05 ± 0.60^a	3 ± 0.86^{ab}	3.3 ± 0.57^a
GU4	3.35 ± 0.88^{ab}	3.6 ± 0.88^a	3.05 ± 0.60^a	2.9 ± 1.12^{ab}	3.1 ± 0.97^a
GU6	2.8 ± 1.11^b	3.05 ± 1.05^a	2.7 ± 1.13^a	2.35 ± 1.09^b	2.5 ± 1.10^b

Values are presented as mean $\pm$ SD. Values with different superscripts within the same columns are statistically significantly different ($p < 0.05$).

Sensory evaluation is a critical parameter in the development of novel food products. In this study, color was closely associated with the appearance of *geblek*. While consumers generally favored a green coloration, excessive darkening, as observed in GU6, resulted in the lowest appearance score among treatments. A similar trend was evident in overall acceptability, with GU6 (highest *Ulva* sp. concentration) receiving the lowest ratings compared to formulations with lower inclusion levels. This decline was primarily attributed to the undesirable taste imparted by *Ulva* sp. at higher concentrations. Previous studies have also noted that seaweed can negatively influence sensory perception due to its characteristic aroma and fishy taste (Sinaga et al., 2024).

CONCLUSION

The supplementation of geblek with *Ulva* sp. represents an innovative approach to developing traditional foods with potential functional properties. The supplemented products exhibited increased fat and ash contents and enhanced antioxidant activity, while protein and crude fiber contents did not change significantly. The incorporation of *Ulva* sp. also influenced the physicochemical characteristics of geblek, particularly its texture and color, which were reflected in the sensory evaluation outcomes. Overall, moderate supplementation with *Ulva* sp. improved selected nutritional and physicochemical characteristics while maintaining acceptable sensory quality, supporting its potential for the development of a traditional food with enhanced functional properties. This study demonstrates the potential utilization of marine resources to increase the value of geblek as a culturally significant traditional food from Kulon Progo while providing opportunities for the development of products with improved nutritional and functional characteristics.

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CONFLICT OF INTEREST

The author states that there is no conflict of interest in the preparation of this article.

AUTHOR CONTRIBUTION

All authors contributed to conceptualization, search and synthesis of literature, interpretation of results, manuscript preparation, and critical review of manuscripts. All authors have read and approved the final version of the manuscript.

GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

The authors declare that Generative Artificial Intelligence (Generative AI) was used solely to assist with language refinement, grammatical correction, and improvement of manuscript readability. All scientific concepts, interpretations, literature synthesis, analyses, and conclusions were developed by the authors. All AI-assisted content was carefully reviewed, verified, and revised by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript.

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