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Original Article

Formulation and characterization of *Halymenia dilatata*-based nori alternative through nutritional, sensory, structural, textural, and functional analyses

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Abstract
The increasing demand for seaweed-based foods has created interest in developing sustainable alternatives to conventional *Porphyra*-based nori using tropical seaweed resources. This study developed a nori-like product from *Halymenia dilatata* and evaluated the effects of glycerin concentration and drying conditions on its nutritional, physicochemical, structural, and sensory properties. Four formulations were prepared using a constant seaweed-to-water ratio (1:10, w/v) with varying glycerin concentrations. The formulation containing 2.5% glycerin and dried at 55°C for 2 h produced sheets with the best pliability, uniformity, and handling characteristics. The optimized product contained low moisture (7.84%), moderate protein (11.62%), high dietary fibre (31.54%), and a mineral-rich ash content (14.87%), with appreciable levels of iron and zinc and a balanced sodium-to-potassium ratio. Sensory evaluation indicated good consumer acceptance for appearance, flavour, texture, and overall acceptability. Structural analyses confirmed the formation of a cohesive polysaccharide network, while biochemical and microbiological analyses demonstrated favourable quality, oxidative stability, and microbial safety. These findings demonstrated that *H. dilatata* could be successfully developed into a nutritious, safe, and acceptable nori-like product with physicochemical characteristics comparable to those of conventional nori, highlighting its potential as a sustainable tropical alternative for value-added seaweed-based food products.

Keywords: amino acid profile; glycerin formulation; *Halymenia dilatata*; nori-like product; proximate composition; sensory evaluation; seaweed processing

1 | INTRODUCTION

The worldwide interest in seaweed-derived foods has increased significantly over the past decades owing to their high nutritional content, functional bioactive compounds, and low environmental footprints (Taboada *et al.* 2013; Sinurat *et al.* 2024). The nori commonly derived from *Porphyra* species is one of the most commercially important seaweed products due to its applications in Asian culinary traditions and a growing global snack industry. Indonesian *Porphyra marcossi* has been identified

as a viable domestic raw material for nori production, yielding products with protein content of 41.49% and 10 detectable amino acids including alanine, glutamic acid, and glycine that contribute to flavor (Loupatty 2015). In India, cultivation of *Porphyra* is not feasible because it mainly thrives in temperate and cold seawaters. Therefore, India and many countries in Southeast Asia depend on imported nori for domestic consumption (Panjaitan *et al.* 2021). *Halymenia dilatata* is a red seaweed (Rhodophyta) growing abundantly in the southeastern coast of India, such as Mandapam and Gulf of Mannar. The plant is recognized for high concentrations of polysaccharides, essential mineral contents, as well as a moderate and balanced amino acid profile (Dawczynski *et al.* 2007; Rondevaldova *et al.* 2023; Yogarajalakshmi and Poonguzhali 2023). Similar film-forming behavior has been demonstrated in red seaweed biopolymers such as *Porphyra columbina*, where stable edible films were successfully developed due to the interaction of polysaccharides and proteins (Cian *et al.* 2014).

Up until now, research on nori substitutes has mostly concentrated on species like *Ulva lactuca*, *Gracilaria*, and *Eucheuma cottonii* (Panjaitan *et al.* 2021; Limonu *et al.* 2024; Sinurat *et al.* 2024). Nori analogues produced from tropical red seaweeds such as *Kappaphycus alvarezii* have demonstrated dietary fiber content of up to 18.6% and antioxidant activity at IC50 values of 59.9 ppm when fortified with bio-active plant ingredients (Limonu *et al.* 2024). Despite the encouraging results of these studies, many of the final products have had drawbacks, such as brittleness, uneven coloration and lower sensory acceptance when compared to commercial nori (Sinurat *et al.* 2024; Panjaitan *et al.* 2021). The incorporation of natural plasticizers such as glycerin has been shown to improve film flexibility, cohesiveness and moisture retention by enhancing water binding capacity and increasing polymer mobility (Müller *et al.* 2008). However, limited information is available on how varying glycerin concentrations and drying conditions influence the quality attributes of *H. dilatata* based nori analogues. Therefore, the present study aimed to develop a nori-like product using *H. dilatata* as the primary raw material, examine the effects of different glycerin levels and processing conditions on its nutritional, physical, and sensory characteristics, and discuss the structural and functional properties of the optimized formulation with those of conventional nori.

2 | METHODOLOGY

2.1 Raw material collection and preparation

The dried *H. dilatata* biomass was procured from the Mandapam RK Algae Centre (Tamil Nadu, India). The seaweed was wild harvested from coastal waters of the Gulf of Mannar and sun-dried under hygienic conditions prior to procurement. Drying was carried out at ambient temperature (30–35°C) until the moisture content was reduced to approximately 10–12%. No chemical preservatives were used during drying. Upon arrival at the laboratory, the dried material was stored in airtight polyethylene containers at room temperature until further use. Before use, the material was carefully cleaned by repeated rinsing with tap water followed by distilled water to eliminate residual sand, salt deposits and external contaminants. The washed seaweed was subsequently immersed in distilled water for two hours, allowing adequate rehydration and softening of the tissue structure.
The hydrated biomass was then subjected to a brief boiling step in distilled water at 1:10 (w/v) ratio for ten minutes. This treatment assisted in removing soluble impurities and produced a softened, cohesive mass suitable for slurry formation. The pre-treatment procedure followed approaches previously reported for nori analogue production from tropical seaweeds (Panjaitan *et al.* 2021; Sinurat *et al.* 2022). After boiling, the mixture was allowed to cool to ambient temperature prior to incorporation into the sheet forming process.

2.2 Preparation of nori-like seaweed sheets

Four formulations (F1–F4) of *H. dilatata* nori-like sheets were prepared using a constant seaweed-to-water ratio (1:10, w/v) while varying the glycerin concentration (0, 1.5, 2.5, and 3.5% w/w based on dry seaweed weight) as shown in Table 1. Formulation F1 served as the control without glycerin, whereas F2, F3, and F4 contained increasing concentrations of glycerin to evaluate its effect on the physical characteristics of the developed sheets. Glycerin was incorporated as a plasticizing agent to modulate sheet flexibility and structural integrity. Previous studies reported that glycerin addition increased elongation and flexibility in seaweed-based nori sheets (Sinurat *et al.* 2021). The hydrated seaweed slurry was homogenized using a blender at 1500 rpm until a uniform paste was obtained. The mixture was evenly spread onto Teflon-coated trays (24 × 22 cm) to prevent adhesion and ensure uniform thickness. The prepared sheets were then subjected to controlled drying conditions for further optimization.

For improved reproducibility, glycerin concentration was also expressed relative to dry seaweed weight. In the optimized formulation (F3), glycerin was incorporated at 2.5% (w/w, based on dry seaweed weight). Expressing glycerin concentration on a dry-weight basis minimizes variability associated with differences in hydration levels of the seaweed biomass and improves reproducibility of the formulation.

2.3 Temperature-time optimization

Drying optimization was conducted by subjecting prepared sheets to five different temperature–time combinations- 45°C for 3 h, 50°C for 2.5 h, 55°C for 2 h, 60°C for 1.5 h and 65°C for 1 h. The influence of drying conditions

on sheet characteristics was evaluated in terms of flexibility, appearance, shrinkage and overall handling properties.

2.4 Proximate composition analysis

All proximate analyses were conducted according to standard procedures (AOAC 2016). All proximate composition analyses were performed in triplicate (n = 3), and the results are expressed as mean ± standard deviation. Comparisons with commercial nori were based on literature reported values from previous studies, rather than direct experimental analysis.

TABLE 1 Formulations of nori-like product from *Halymenia dilatata*.

Formulation	Seaweed:Water ratio (w/v)	Glycerin (% w/w, based on dry seaweed weight)	Description
F1	1:10	0.0	Control (no glycerin)
F2	1:10	1.5	Slightly plasticized
F3	1:10	2.5	Moderately plasticized
F4	1:10	3.5	Highly plasticized

Moisture content: According to the AOAC official methodology (Method 950.46), the samples were dried in a hot air oven at 105±1°C until they attained a constant mass in order to quantify the moisture content using a standard gravimetric process. Each sample's moisture percentage was determined using the weight loss after drying (AOAC 2016).

Crude protein: The Kjeldahl method which gauges total nitrogen was used to calculate crude protein concentration. Concentrated sulfuric acid was used to digest the samples in the presence of a catalytic combination. The digest was then neutralized and steam distilled. A standard conversion factor of 6.25 was used to measure and transform the nitrogen produced during distillation into protein (AOAC Method 984.13)(AOAC 2016).

Crude fat: Petroleum ether was used as the extraction solvent in a Soxhlet extraction process to determine the total fat content. For 6 to 8 h, the dried samples were continually refluxed which allowed the solvent soluble lipids to be completely removed. To determine the total fat content, the solvent was evaporated after extraction and the leftover lipid residue was dried and weighed (AOAC Method 920.39)(AOAC 2016).

Ash content: A pre weighed part of the sample was heated in a muffle furnace at 550±15°C until a stable grey white residue was formed in order to measure the ash concentration. Ash content was defined as the amount of inorganic materials that remained after full combustion (AOAC Method 942.05)(AOAC 2016).

Dietary fiber: Dietary fibre was determined using an enzymatic gravimetric procedure following the AOAC guidelines (AOAC Method 985.29). This method involved digestion of sample with α-amylase, protease and amyloglucosidase to break down starch and protein under controlled conditions. After the enzymatic treatment, the remaining insoluble fraction was separated through filtration and thoroughly washed with warm distilled water followed by ethanol and acetone to remove any residual soluble material. The residue was then dried to a constant weight. Corrections for ash and residual protein were applied and final dietary fibre content was calculated (AOAC 2016).

Carbohydrate content: Carbohydrate content was calculated by difference according to AOAC procedures. An indirect assessment of the carbohydrate fraction in the sample was obtained by deducting the combined proportions of moisture, ash, protein and fat from 100% to determine the total carbohydrate percentage (AOAC 2016).

2.5 Amino acid profile

The amino acid composition of the *H. dilatata*-based nori-like product was determined following acid hydrolysis using 6 N hydrochloric acid (HCl) at 110°C for 24 h in vacuum-sealed hydrolysis tubes (Ishida *et al.* 1981). Approximately 100 mg of dried sample was hydrolysed and subsequently prepared for chromatographic analysis.

After hydrolysis, aliquots were evaporated to dryness and reconstituted in 0.1 N HCl prior to analysis. Amino acids were quantified using a liquid chromatography–mass spectrometry (LC–MS) system (Agilent Technologies, USA) equipped with a Poroshell HPH C18 column (4.6 × 100 mm, 2.7 µm). Detection and identification were carried out by comparing retention times and fragmentation patterns with authenticated amino acid standards.

It is important to note that tryptophan was not quantified in the present study, as it is susceptible to degradation under acidic hydrolysis conditions. Therefore, only acid-stable amino acids are reported. Final amino acid concentrations were expressed as mg/g dry weight. Amino acid analysis was performed in single determination.

2.6 Mineral content

The mineral profile of the developed product was assessed using a wet digestion procedure (AOAC 2016). A 0.5 g portion of the dried, homogenized sample was

transferred into a clean digestion tube and treated with 10 mL of concentrated nitric acid (HNO_3). The mixture was allowed to pre-digest overnight at room temperature after which it was heated on a digestion block at 120°C until the solution became clear, indicating substantial removal of organic matter. Once cooled, 2 mL of perchloric acid ($HClO_4$) was added to facilitate complete oxidation of residual organics, and heating was continued until the appearance of dense white fumes signaled the completion of digestion.

After allowing the digest to cool, undissolved particles were removed by filtering it through filter paper (Whatman No. 42) and diluting it to 50 mL with deionized water. An Atomic Absorption Spectrophotometer (Perkin Elmer AAnalyst 400, USA) equipped with element specific hollow cathode lamps was used to quantify minerals. Instrumental parameters, including wavelength, slit width, lamp current, and fuel oxidant ratios, were tuned separately for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe), and zinc (Zn). Calibration standards were prepared using commercially certified multi-element standard stock solutions (1000 mg/L for each element; HiMedia Laboratories Pvt. Ltd., Mumbai, India). Working standard solutions were obtained by serial dilution of the stock solution with 2% (v/v) nitric acid to generate appropriate calibration ranges for each element analyzed. Calibration curves were constructed using at least five concentration levels, and linearity was confirmed with correlation coefficients (R^2) greater than 0.995. Blanks were analyzed alongside samples to monitor potential contamination and baseline drift.

Measurements were recorded after samples were nebulized into the AAS flame at a flow rate of 5 mL/min. Mineral concentrations were calculated from the respective calibration plots using WinLab32 software for data gathering and processing. After adjusting for dilution and sample mass, all values were presented on a % w/w (dry basis). Mineral analysis was performed on the optimized formulation (F3).

2.7 Sensory evaluation

Sensory evaluation of the prepared sheets was conducted using a 9-point hedonic scale (9 = like extremely; 1 = dislike extremely) following standard sensory evaluation procedures (Meilgaard *et al.* 2016). A total of 25 panelists participated voluntarily where they were screened to ensure absence of known seafood allergies and provided informed consent prior to evaluation.

Samples of the optimized formulation (F3) were cut into uniform portions and presented at ambient temperature. Each sample was coded using random three digit numbers to minimize bias and served in a randomized order. Drinking water was provided to panelists for palate cleansing between evaluations. Panelists were asked to rate appearance, flavour, taste, texture and overall acceptability using the hedonic scale. Sensory scores were recorded individually and compiled. Results are expressed as mean ± standard deviation (n = 25).

2.8 Structural analysis

The microstructural features of the developed product were examined using Scanning Electron Microscopy (SEM). Small sections of each sample were affixed to aluminum stubs with double sided carbon adhesive and a thin application of conductive silver paint was used to minimize surface charging during imaging. Prior to observation, the mounted samples were sputter coated with a fine layer of gold to enhance electrical conductivity and image clarity.

SEM analysis was carried out using a JEOL JSM-6390LV microscope (JEOL Ltd., Japan) operated at an accelerating voltage of 20 kV. Images were captured at magnifications between 500× to 5000× allowing detailed visualization of the sheet's surface architecture. This examination provided insights into the structural uniformity, fiber distribution, and overall physical quality of the finished product. Representative SEM micrographs of the optimized formulation are presented.

2.9 Textural properties

Texture Profile Analysis (TPA) of the developed sheets was performed using a TA-XT Plus Texture Analyzer (Stable Micro Systems, UK). Samples were positioned centrally on the test platform, and compression was applied with a P/75 cylindrical probe. A two-cycle compression sequence was used to simulate the mechanical actions associated with mastication. During testing, the instrument recorded the primary textural attributes like hardness, springiness, cohesiveness, and chewiness. All operational parameters including test speed, compression distance and trigger force were standardized to ensure consistent measurements. Analyses were conducted at ambient laboratory temperature, and the resulting force–time curves were processed using the manufacturer's software to derive the textural profiles. Texture Profile Analysis (TPA) was performed on the optimized formulation (F3).

2.10 Functional characterization

The functional groups present in the developed sheet were characterized using Fourier Transform Infrared Spectroscopy (FTIR). For pellet preparation, the sample was finely ground and blended with spectroscopic-grade potassium bromide (KBr) in a 1:9 ratio ensuring thorough homogenization. The homogenized powder was placed in a die assembly and compressed using a hydraulic press, yielding a clear, uniform pellet suitable for infrared transmission. After carefully removing the pellet from the die, it was positioned on the instrument's sample holder for spectral acquisition. Spectra were recorded over 32 scans at a 4 cm^{-1} resolution, spanning the range of 600–

4000 cm^{-1}. The resulting absorption profiles were interpreted to identify characteristic functional groups and molecular bonds based on their diagnostic peak positions. A representative FTIR spectrum of the optimized formulation is presented (Barth 2007).

2.11 Biochemical analysis

The biochemical quality of the product was evaluated through the estimation of Free Fatty Acids (FFA), Peroxide Value (PV) and Thiobarbituric Acid Reactive Substances (TBARS). Free fatty acid content was determined (Jacobs 1958), wherein the lipid extract was titrated against sodium hydroxide using phenolphthalein as an indicator, and the results were expressed as percentage of oleic acid. The peroxide value was assessed using the iodometric titration (Olley and Lovern 1960), which measures the amount of iodine liberated from potassium iodide by peroxides present in the lipid fraction. The results were recorded as milliequivalents of peroxide per kilogram of fat. Lipid oxidation was further evaluated using the TBARS assay based on the distillation method (Zeb and Ullah 2016). This method involved the reaction of malondialdehyde (MDA), a secondary lipid oxidation product, with thiobarbituric acid (TBA) under acidic and high-temperature conditions to form a pink chromogen, which was measured spectrophotometrically at 532 nm and TBARS values were expressed in micromoles per gram (µM/g) of sample. All biochemical analyses were performed in triplicate (n = 3), and the results are expressed as mean ± standard deviation.

2.12 Microbial analysis

The microbial quality of the product was assessed by determining Total Plate Count (TPC) and Total Fungal Count (TFC) following the standard methods described in the Compendium of Methods for the Microbiological Examination of Foods (Vanderzant and Splittstoesser 1992). For enumeration, 25 grams of the sample were aseptically weighed and homogenized with 225 ml of sterile physiological saline solution (0.85% NaCl) to prepare a primary dilution. Serial decimal dilutions were then made using 9 ml of sterile saline for each step.

From the appropriate dilutions, 0.1 ml aliquots were plated onto Nutrient Agar (NA) for Total Plate Count (TPC) and Potato Dextrose Agar (PDA) for Total Fungal Count (TFC) under aseptic conditions. The plates were labelled and incubated at 37°C for 24 to 48 h. Microbial loads were quantified and expressed as colony-forming units per gram (cfu/g) of sample. Microbiological analyses were performed in triplicate (n = 3), and the results are expressed as mean ± standard deviation.

3 | RESULTS AND DISCUSSION

3.1 Formulation and drying optimization

Among the four formulations evaluated under a constant seaweed-to-water ratio (1:10, w/v), Formulation F3 containing 2.5% glycerin produced the most desirable sheet characteristics from *H. dilatata*. During preliminary trials, the control sample (F1) lacked flexibility and tended to crack during drying, while F2 showed only marginal improvement in pliability. In contrast, F3 consistently produced sheets with balanced flexibility, uniform surface appearance, and sufficient mechanical strength, without exhibiting excessive softness or tackiness. The highest glycerin level (F4, 3.5%) resulted in overly soft sheets that were difficult to handle and more prone to deformation during drying. Based on these observations, F3 was selected as the optimized formulation for subsequent analyses. Similar findings were reported by Sinurat *et al.* (2021), where increasing glycerin concentration improved elongation and flexibility of seaweed-based nori sheets; however, excessive glycerin levels adversely affected product characteristics.

Drying optimization further influenced sheet characteristics. Sheets dried at 45–50°C retained higher residual moisture, resulting in softer surfaces and reduced structural firmness. In contrast, drying at 60–65°C produced fragile sheets with increased brittleness and slight surface darkening. Among the tested conditions, drying at 55°C for 2 h yielded uniformly coloured sheets with good pliability and minimal warping. Therefore, 55°C for 2 h was selected as the optimal drying condition for further characterization studies.

3.2 Product appearance

The appearance of the developed nori-like product before and after roasting, along with commercial nori, is presented in Figure 1. The optimized sheet exhibited a uniform surface, good structural integrity, and an appearance comparable to commercial nori. Roasting resulted in a darker colour and improved surface characteristics, enhancing its visual similarity to conventional nori.

3.3 Proximate composition

The proximate composition provides insight into the nutritional characteristics of the product and its suitability as a plant-based seaweed sheet (Table 2). The moisture content of the finished sheets was 7.84±0.42%, which is comparable to dehydrated seaweed products produced under controlled drying conditions. Low moisture content is desirable because it reduces water activity and helps maintain product stability during storage, a trend commonly observed in nori and other seaweed-based sheet products (Taboada *et al.* 2013; Sinurat *et al.* 2024). The moisture level of the developed *H. dilatata* sheet was comparable to values reported for commercial nori products, where compositional and functional properties vary depending on raw material quality and processing conditions (Kurakake *et al.* 2021; Jung *et al.* 2022).

The protein content was measured at 11.62±0.33%,

reflecting the moderate protein characteristics of red seaweeds. Although lower than commercial nori, the obtained value is consistent with previous reports on *H. dilatata*, which documented protein levels ranging from 8--13% on a dry-weight basis (Yogarajalakshmi and Poonguzhali 2023). The observed protein content demonstrates that the developed product retains the moderate protein characteristics commonly associated with edible red seaweeds (Wong and Cheung 2000; Taboada *et al.* 2013). Traditional nori made from *Porphyra* species contains protein levels of 25–50% dry weight and biologically active compounds associated with health benefits (Noda 1993).

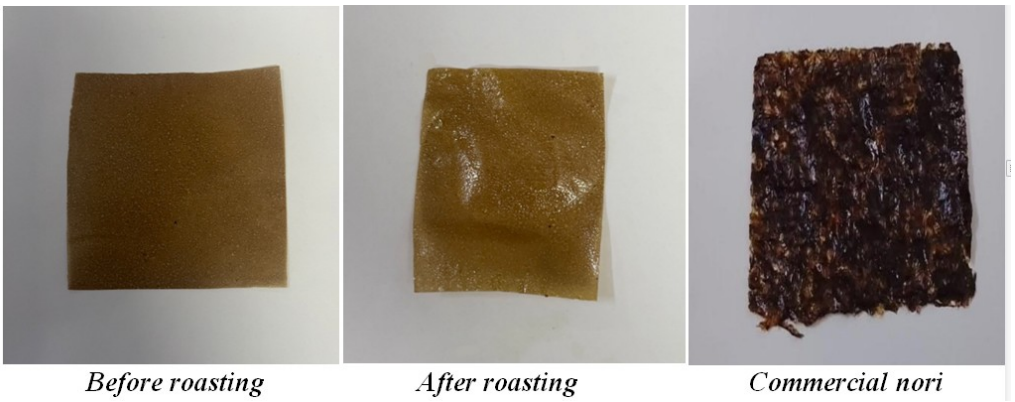

FIGURE 1 Nori-like product from *Halymenia dilatata* and commercial nori.

TABLE 2 Proximate composition of the nori-like product from *Halymenia dilatata* (*n* = 3).

Parameter	Value (%)
Moisture	7.84 ±0.42
Protein	11.62±0.33
Fat	0.92±0.05
Ash	14.87±0.61
Carbohydrates	64.75±1.12
Dietary fiber	31.54±0.94

The fat content of the product was 0.92±0.05%, consistent with the inherently low lipid content reported for red seaweeds, including *Halymenia* species (Yogarajalakshmi and Poonguzhali 2023). Seaweeds generally contain low lipid levels, and similar low-fat values have also been reported in nori products developed from tropical seaweeds (Taboada *et al.* 2013; Listyaningrum and Hidayatulloh 2024).

Ash content representing the total mineral fraction was relatively high at 14.87±0.61 %. This value is characteristic of mineral-rich seaweeds and is comparable to findings reported in other seaweed-based nori products (Taboada *et al.* 2013; Sinurat *et al.* 2024). The elevated ash value corresponds with mineral profile of *H. dilatata* particularly abundance of sodium, potassium, calcium, magnesium, iron and zinc in previous studies (Xavier and Jose 2020; Yogarajalakshmi and Poonguzhali 2023).

Carbohydrates calculated by difference accounted for 64.75±1.12% of the dry weight. This aligns with the carbohydrate-rich nature of red seaweeds, particularly species within the *Halymenia* genus, which have been reported to contain structural polysaccharides such as sulfated galactans that contribute to their functional properties (Fenoradosoa *et al.* 2009). The calculated carbohydrate value represents total carbohydrate by difference, which includes the dietary fibre fraction. Dietary fibre was determined separately to provide additional nutritional information.

Dietary fiber constituted 31.54±0.94% reflecting the substantial fiber content commonly reported in edible seaweeds (Ortiz *et al.* 2006; Dawczynski *et al.* 2007). A comparative analysis of commercially available edible seaweed products revealed that dietary fiber constitutes the largest fraction (15–75% dry weight) and that glutamic acid consistently dominates the free amino acid pool across red, brown, and green seaweeds, contributing substantially to their characteristic umami flavor (Dawczynski *et al.* 2007). High dietary fiber content is considered one of the major nutritional advantages of seaweed-based foods, as dietary fiber has been associated with improved gut health, enhanced satiety, and better glycemic regulation (Cherry *et al.* 2019). Commercial nori also contains considerable dietary fiber, placing the developed product within the expected nutritional range of edible seaweed sheets (Taboada *et al.* 2013).

Alternative seaweed-based nori products using tropical species such as *Sargassum* sp. and *Eucheuma spinosum* have demonstrated comparable crude fiber content (11.7%) and water content (15.67%) to commercial nori, confirming the viability of non-*Porphyra* species for nori production (Faris *et al.* 2019). Nori-like products developed from mixtures of red and green tropical seaweeds have demonstrated dietary fiber contents in the range of 29–30%, which exceeds the fiber content of commercial *Porphyra* based nori (approximately 23%), highlighting the fiber enrichment potential of tropical species (Erniati *et al.* 2018).

Overall, the proximate composition confirms that

the product is nutritionally comparable to commercial nori and demonstrates the characteristic seaweed profile of high carbohydrates and minerals, moderate protein, low fat and low moisture. These findings support *H. dilatata* as a suitable alternative for nori production.

3.4 Mineral composition

The microelement fraction was also nutritionally significant (Table 3). The product contained iron (Fe) at 0.74%, zinc (Zn) at 0.20%, manganese (Mn) at 0.0012%, and copper (Cu) at 0.042%. The retention of Fe and Zn is particularly noteworthy, as previous studies have reported appreciable concentrations of these trace minerals in *H. dilatata* (Rondevaldova *et al.* 2023 Yogarajalakshmi and Poonguzhali 2023). Iron content in raw *H. dilatata* has been reported to reach 1.24%, and despite processing-related reductions, the developed product retained substantial levels of iron and zinc. The sodium-to-potassium (Na/K) ratio of the product was calculated to be 2.16, comparable to ratios reported for raw *H. dilatata* (2.53) (Yogarajalakshmi and Poonguzhali 2023). A sodium-to-potassium (Na/K) ratio below 4.0 is considered nutritionally desirable, as higher potassium relative to sodium intake is associated with reduced hypertension risk (He and MacGregor 2008). Commercial nori species such as *Porphyra tenera* have similarly been reported to contain substantial levels of minerals, including sodium, potassium, calcium, magnesium, iron, and zinc (Rupérez 2002).

Overall, the mineral composition of the product demonstrated nutritional characteristics comparable to commercial nori. The high Fe and Zn contents, balanced Na/K ratio highlight the suitability of *H. dilatata* as a promising tropical seaweed for developing nutritious nori alternatives.

TABLE 3 Mineral composition of the nori-like product from *Halymenia dilatata* (values represent a single analytical determination of the optimized formulation).

Mineral	% w/w (dry basis)
Sodium (Na)	5.89
Potassium (K)	2.72
Calcium (Ca)	0.83
Magnesium (Mg)	0.54
Iron (Fe)	0.74
Zinc (Zn)	0.20
Manganese (Mn)	0.0012
Copper (Cu)	0.042

3.5 Amino acid profile

The amino acid profile demonstrates the presence of both essential and non-essential amino acids, consistent with previously reported compositions of edible red seaweeds (Table 4) (Ortiz *et al.* 2006; Dawczynski *et al.* 2007). Amino acid concentrations were determined from hydrolyzed samples, whereas crude protein was estimated by the Kjeldahl method from total nitrogen; therefore, the two values were generated by different analytical approaches and are not directly comparable (Kjeldahl 1883; Mariotti *et al.* 2008).

TABLE 4 Amino acid composition of the nori-like product from *Halymenia dilatata* (values represent a single analytical determination of the optimized formulation).

Amino acid	Product of this study (mg/g dry weight)
Essential	
Histidine	0.92
Isoleucine	1.48
Leucine	2.84
Lysine	2.03
Methionine	1.17
Phenylalanine	1.98
Threonine	1.74
Valine	2.11
Non-essential	
Alanine	3.18
Arginine	2.86
Aspartic acid	3.94
Cysteine	0.54
Glutamic acid	5.82
Glycine	7.36
Proline	3.41
Serine	2.28
Tyrosine	0.67

Among the essential amino acids, leucine (2.84 mg/g), valine (2.11 mg/g), and lysine (2.03 mg/g) were present in comparatively higher concentrations. The product also contained measurable levels of threonine, methionine, phenylalanine, and isoleucine, which further contribute to its essential amino acid profile (Dawczynski *et al.* 2007; Lee *et al.* 2012). Non-essential amino acids were present in higher proportions, which is a trend commonly observed in Rhodophyta species (Ortiz *et al.* 2006; Fleurence *et al.* 2012). Notably, glutamic acid (5.82 mg/g) and aspartic acid (3.94 mg/g) were abundant, thus contributing to the umami taste typical of seaweed-based foods (Fleurence *et al.* 2012; Lee *et al.* 2012). Significant quantities of glycine (7.36 mg/g) and alanine (3.18 mg/g) were also detected. The amino acid distribution observed aligns with patterns reported in earlier studies, where red seaweeds are characterized by relatively higher proportions of glutamic acid, aspartic acid, and other non-essential amino acids (Černá 2011; Fleurence *et al.* 2012).

Previous studies on *Porphyra* spp. have similarly reported the presence of essential amino acids such as leucine and lysine, although direct comparison remains limited because reported values are often expressed on a protein basis rather than dry weight (Dawczynski *et al.* 2007; Lee *et al.* 2012). The presence of leucine (2.84

mg/g), valine (2.11 mg/g), and lysine (2.03 mg/g) in *H. dilatata* is consistent with the general amino acid profiles reported for edible red seaweeds and commercial nori products (Lee *et al.* 2012).

According to FAO (2013) protein quality guidelines, leucine, lysine, and valine are indispensable amino acids that must be present in adequate proportions in dietary proteins. Although the present study quantified only acid-stable amino acids, the presence of these essential amino acids indicates that *H. dilatata* shares amino acid characteristics commonly reported in edible red seaweeds, including nori (Ortiz *et al.* 2006; Dawczynski *et al.* 2007).

3.6 Sensory evaluation

The sensory quality was evaluated using a 9-point hedonic scale to assess appearance, flavour, taste, texture, and overall acceptability. A total of 25 panelists participated in the evaluation. The mean sensory scores obtained were 7.88±0.83 for appearance, 7.96±0.75 for flavour, 7.84±0.67 for taste, 8.48±0.65 for texture, and 8.36±0.70 for overall acceptability (Figure 2). All values are expressed as mean ± standard deviation (n = 25).

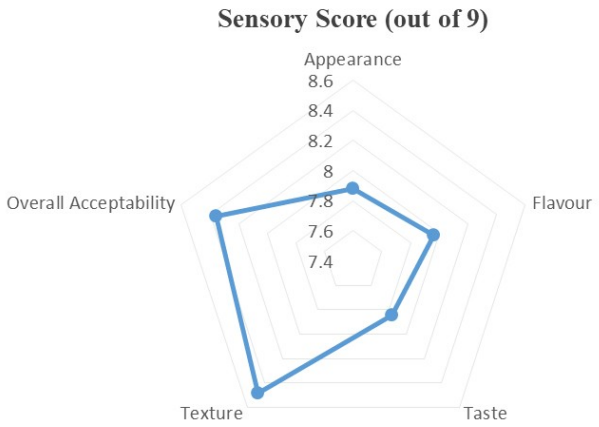

FIGURE 2 Sensory scores of nori-like product from *Halymenia dilatata*, evaluated using a 9-point hedonic scale (n = 25; mean±SD).

The scores across the evaluated attributes indicate positive panelist responses under the experimental conditions. The appearance score (7.88) reflects the uniform surface characteristics and consistent brown coloration achieved at the optimized drying temperature of 55°C. Flavour and taste scores (7.96 and 7.84, respectively) indicate favorable sensory acceptance of the developed product. Similar sensory acceptance scores have been reported for nori analogues developed from *Ulva lactuca* and *Gracilaria* (7.5–8.5) (Listyaningrum and Hidayatulloh 2024; Sinurat *et al.* 2024).

Among the evaluated parameters, texture recorded the highest mean score (8.48), indicating favorable crispness and flexibility. This may be partly attributed to glycerin incorporation, which has previously been reported to improve flexibility and reduce brittleness in seaweed-based nori sheets (Sinurat *et al.* 2021). The overall acceptability score (8.36) indicates that the optimized formulation was well received under the conditions evaluated.

3.7 Structural analysis

Scanning Electron Microscopy was used to examine the microstructural properties providing insight into surface morphology and structural integrity following sheet formation and drying. The micrographs captured at progressively higher magnifications of 500×, 1000×, 2500× and 5000× reveal distinct changes in texture, compaction and fibrillar organization (Figure 3). These observations help explain the mechanical behavior and sensory characteristics of the final product.

Image A (500×): At the lowest magnification, the surface appears as a loosely interwoven matrix with broad and uneven layers characteristic of gel derived seaweed films. The sheet displays visible folds and shallow depressions formed during the dehydration step. These irregularities are expected in polysaccharide-rich red seaweeds, particularly species within the Halymenia genus that have been reported to contain sulfated galactans (Fenoradosoa et al., 2009). Similar cohesive film structures have been reported in Porphyra columbina biopolymer films, where interactions among seaweed-derived biopolymers contributed to stable film formation (Cian et al., 2014). The overall appearance reflects a partially cohesive structure that may have contributed to the observed sheet pliability. Similar improvements in flexibility following glycerin incorporation have been reported in seaweed-based nori sheets (Sinurat et al., 2021).

Image B (1000×): At 1000×, the network becomes more defined revealing elongated fibrillar strands intertwined with flattened plate like regions. Such features are commonly observed in dried red seaweed matrices following dehydration. The presence of micro-voids and channels likely resulted from water loss during the drying process. This porous microstructure may have contributed to the moderate flexibility and crisp texture observed during sensory evaluation.

Image C (2500×): At higher magnification, the sample surface shows tighter aggregation of polysaccharide strands with fewer open cavities than in the lower magnification images. The sheet appears more compact, with smoother regions transitioning into coarse fibrous bundles. This compaction reflects the collapse of hydrated cell compartments during the boiling and dehydration stages. The improved density at this scale may have contributed to better structural integrity of the final sheet.

Image D (5000×): The highest-magnification image reveals a highly compacted surface with closely fused granules and minimal visible porosity. The smooth undulating appearance suggests the formation of a compact and stable sheet matrix during drying. This micro scale fusion indicates successful sheet consolidation during drying and is associated with improved structural stability. The absence of large voids indicates improved structural uniformity under the optimized drying condition of 55°C.

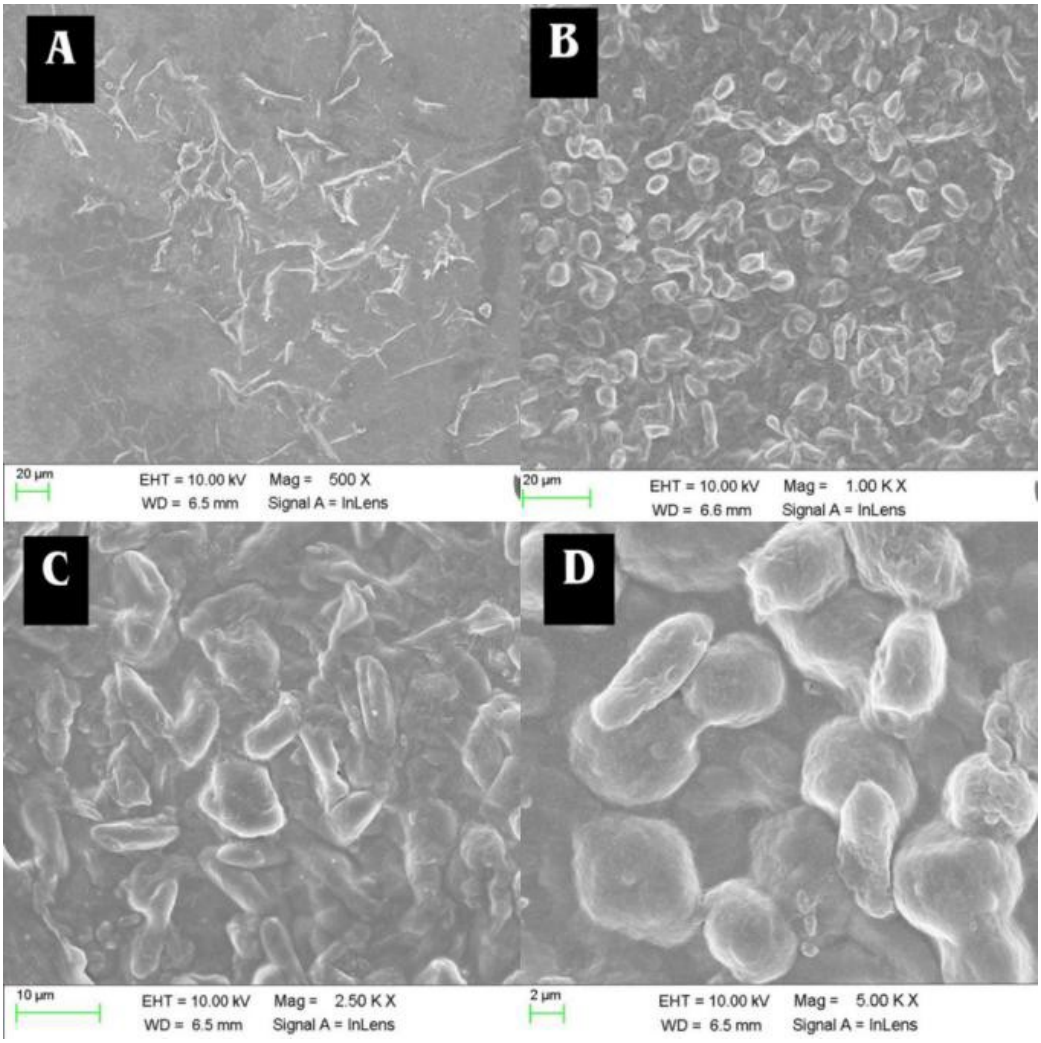

FIGURE 3 SEM images of the nori-like product from *Halymenia dilatata* at different magnifications. (A) SEM image at 500×, showing a loosely interwoven polysaccharide matrix with broad, uneven layers formed during dehydration. (B) SEM image at 1,000×, revealing a more defined fibrillar network with elongated strands and micro-voids indicative of moisture-migration pathways. (C) SEM image at 2,500×, showing tighter aggregation of polysaccharide bundles and reduced porosity due to compaction during thermal processing. (D) SEM image at 5,000×, displaying a densely fused, compact surface with minimal porosity, reflecting strong polysaccharide consolidation during drying.

3.8 Textural properties

The Texture Profile Analysis (TPA) insights into their mechanical strength and consumer relevant eating characteristics (Table 5). The hardness was measured at 612.45 g, indicating a firm sheet structure while maintaining sufficient flexibility for handling. The relatively firm texture may be associated with the compact microstructure observed in SEM analysis following controlled drying at 55°C, since drying conditions and seaweed incorporation can strongly influence compactness and texture in seaweed-based products (Jung *et al.* 2022; Sravani *et al.* 2023).

The fracturability value of 428.73 g indicates moderate brittleness, an attribute desirable in dried seaweed sheets where a balance between crispness and structural stability is desirable. Similar textural behavior has been reported in nori-like products developed from *Ulva lactuca* and *Gracilaria* spp., where formulation and glycerin addition affected sheet texture (Sinurat *et al.* 2022). Moisture content has been reported to significantly influence the crispness and mechanical properties of dried *Porphyra* product (Jung *et al.* 2022). Differences in structural and textural properties among seaweed sheets are often influenced by species-specific polysaccharide composition and raw material quality (Kurakake *et al.* 2021).

Gumminess and Chewiness were recorded at 156.32 g and 92.47 respectively, indicating moderate resistance during mastication. These values may be associated with the cohesive matrix formed during sheet preparation. Similar cohesive structural behaviour has been reported

in edible films prepared from *Porphyra columbina* interactions among seaweed-derived biopolymers contributed to stable film formation (Cian *et al.* 2014).

Springiness and Cohesiveness measured at 0.684 and 0.322 respectively, indicating moderate elastic recovery and internal bonding strength. The resilience value of 0.178 suggests limited structural recovery upon deformation, which is expected in dehydrated sheet products. The observed flexibility of the developed sheet may also be attributed to glycerin incorporation, as previous studies have shown that glycerin improves elongation and reduces brittleness in seaweed-based nori sheets (Sinurat *et al.* 2021). Overall, the textural attributes indicate a desirable balance of firmness, elasticity and cohesive strength, supporting the suitability of *H. dilatata*.

TABLE 5 Texture profile analysis of nori-like product from *Halymenia dilatata* (values represent a single analytical determination of the optimized formulation).

Texture parameter	Results
Force (g)	575.33
Hardness (g)	612.45
Fracturability (g)	428.73
Area	398.54
Springiness	0.684
Cohesiveness	0.322
Gumminess (g)	156.32
Chewiness	92.47
Resilience	0.178

3.9 Functional characterization

The FTIR spectrum shows distinct absorption bands representing the principal functional groups present in the H. dilatata nori-like sheet (Figure 4) (Krimm and Bandekar 1986; Barth 2007). A broad absorption band in the region of 3200–3500 cm^{-1} was observed and attributed to O–H stretching vibrations associated with hydroxyl groups present in seaweed polysaccharides and bound moisture. Similar broad hydroxyl bands have been reported in edible films prepared from *Porphyra columbina* biopolymers (Cian *et al.* 2014). The peaks observed at 2920–2850 cm^{-1} were attributed to asymmetric and symmetric C–H stretching vibrations of aliphatic carbon chains, indicating the presence of aliphatic functional groups within the product matrix (Krimm and Bandekar 1986). A strong absorption band near 1640 cm^{-1} corresponded to the Amide I region, primarily associated with C=O stretching vibrations of peptide bonds, while the band around 1540–1550 cm^{-1} represented the Amide II region related to N–H bending and C–N stretching vibrations. These amide bands indicate the presence of residual protein components retained after processing and are consistent with the protein content identified during proximate analysis (Krimm and Bandekar 1986; Barth 2007).

The absorption bands at 1210–1260 cm^{-1} attributed to sulfate ester S=O stretching vibrations are well-established diagnostic peaks for sulfated polysaccharides in red seaweeds, with characteristic positions for ester sulfate groups in galactans confirmed by reference vibrational spectroscopy studies (Pereira *et al.* 2009). Similar sulfated galactan structures have been reported in species belonging to the *Halymenia* genus (Fenoradosoa *et al.* 2009). Additional peaks observed between 1030 and 1140 cm^{-1} corresponded to C–O–C stretching vibrations of glycosidic linkages, indicating the presence of carbohydrate backbone structures. The absorption peak near 930 cm^{-1} further suggests the presence of 3,6-anhydrogalactose residues commonly associated with red algal polysaccharides, while lower frequency absorptions between 610 and 700 cm^{-1} were attributed to ring bending vibrations of substituted carbohydrate structures (Krimm and Bandekar 1986).

Comparable FTIR characteristics have been reported in edible films prepared from *Porphyra columbina*, where hydroxyl, sulfate, glycosidic, and protein-associated functional groups contributed to film stability (Cian *et al.* 2014). Overall, the FTIR profile confirms the presence of hydroxyl, sulfate, glycosidic, and amide functional groups in the developed product, indicating that the major biochemical constituents of *H. dilatata* were retained after processing and contributed to the formation of a stable nori-like sheet.

3.10 Biochemical analysis

The biochemical stability was assessed through measurements of free fatty acids (FFA), peroxide values (PV) and thiobarbituric acid reactive substances (TBARS) as in Table 6, which together provide an assessment of lipid oxidation status and overall chemical stability. Free fatty acid content was determined by alkali titration following standard procedures (Jacobs 1958) and was recorded at low levels, which is consistent with the inherently low fat content of the developed product (0.92%).

Peroxide value was determined using the iodometric method (Olley and Lovern 1960) and reflects the formation of primary lipid oxidation products, particularly hydroperoxides generated during the early stages of oxidative rancidity. The peroxide value of the developed product remained within acceptable limits, indicating minimal primary lipid oxidation. Similar observations were reported in dried *Porphyra umbilicalis* and *Ulva fenestrata*, where lipid oxidation remained limited under controlled drying conditions and low moisture levels (Harrysson *et al.* 2021).

TBARS values were determined using the distillation method (Zeb and Ullah 2016) and expressed as micromoles of malondialdehyde equivalents per gram of sample. TBARS analysis measures malondialdehyde, a secondary lipid oxidation product formed during the breakdown of primary oxidation compounds under ther-

mal and oxidative conditions (Zeb and Ullah 2016). The low TBARS values obtained in the present study indicate minimal secondary lipid oxidation in the developed product. Lipid oxidation in marine-derived products has similarly been reported to be strongly influenced by lipid content and processing conditions (Secci and Parisi 2016). Collectively, the low FFA, PV, and TBARS values indicate that the developed nori-like sheet from *H. dilatata* maintained good chemical stability under the optimized processing conditions.

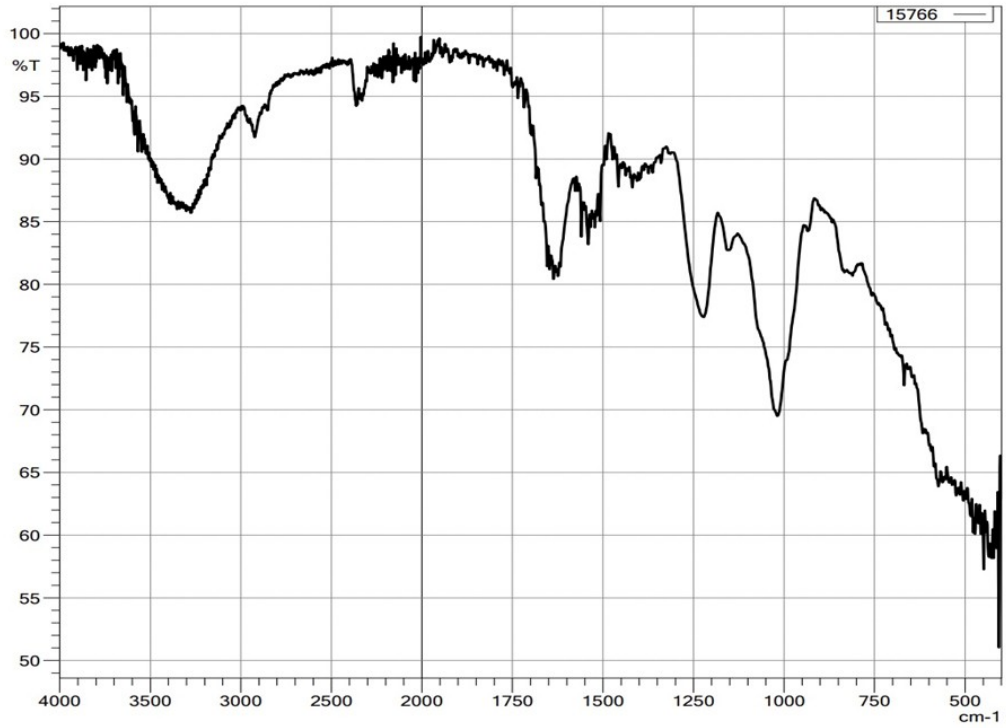

FIGURE 4 FTIR spectrum of the nori-like product from *Halymenia dilatata*.

TABLE 6 Biochemical analysis of the nori-like product from *Halymenia dilatata* (*n* = 3).

Parameter	Value
Free fatty acids (FFA)	0.32±0.05% (as oleic acid)
Peroxide value (PV)	0.98±0.14 meq/kg fat
TBARS	0.36±0.06 µM/g

3.11 Microbial analysis

The microbial quality (Table 7) was evaluated through Total Plate Count (TPC) and Total Fungal Count (TFC) immediately after processing. The microbial quality of the product was assessed through Total Plate Count (TPC) and Total Fungal Count (TFC) determination following standard procedures (Vanderzant and Splittstoesser 1992). Microbial counts for both TPC and TFC remained well within acceptable limits for dried seaweed food products. Drying has been recognized as one of the most effective processing methods for reducing microbial loads in seaweed products by lowering water activity and inhibiting microbial proliferation (Løvdal *et al.* 2021). The drying condition applied in the present study (55°C for 2 h), together with the low final moisture content of 7.84%, likely contributed to the microbial stability of the developed product. The low TFC values further indicate effective control of mould contamination, which is a common spoilage concern in dried plant-based products. However, the present study evaluated microbial quality only at the initial stage (Day 0). Further storage studies are required to confirm long-term microbiological and textural stability under commercial storage conditions.

TABLE 7 Microbial analysis of the nori-like product from *Halymenia dilatata* (*n* = 3).

Parameter	Value (CFU/g)
Total plate count	420±95
Total fungal count	28±11

5 | CONCLUSIONS

The nori-like product from *H. dilatata* demonstrated desirable nutritional, structural, and sensory characteristics. Its moderate protein content, low fat levels and reduced moisture may contribute to improved shelf stability, while the high ash and dietary fibre contents reflect the mineral and polysaccharide rich nature of the seaweed. The product retained essential minerals and the presence of essential and non-essential amino acids characteristic of red macroalgae. SEM imaging confirmed a well consolidated sheet structure with compact polysaccharide domains

and FTIR analysis verified the presence of key functional groups like hydroxyl, sulfate ester, amide and glycosidic linkages thus supporting its structural integrity. Texture profile analysis showed adequate strength, flexibility and chewability, consistent with desirable nori-like sheet characteristics. Sensory evaluation revealed high acceptability across appearance, taste, texture and overall acceptance. The findings indicate that *H. dilatata* can be processed into a nori-like sheet with desirable physicochemical and sensory characteristics. Further storage and large-scale consumer studies are required to confirm long-term stability and commercial feasibility. Although the present study provides detailed physicochemical and sensory characterization, direct comparative analysis with commercial nori was not performed and should be considered in future investigations.

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ETHICAL APPROVAL

The study protocol was approved by the Ethics Committee of the Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Nagapattinam (TNJFU). All participants involved in the sensory tests for the product provided informed consent before the beginning of the study. Participants gave this consent via the statement, "I am aware that my responses are confidential, and I agree to participate in this survey," where an affirmative reply was required to enter the survey. They were able to withdraw from the study at any time without giving a reason. The products tested were safe for consumption.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

Conceptualization: C E Bridgete Princey, P Ganesan; Methodology: C E Bridgete Princey, P Ganesan; Formal analysis and investigation: C E Bridgete Princey, P Ganesan; Writing – original draft preparation: C E Bridgete Princey ; Writing – review and editing: C E Bridgete Princey, P Ganesan, L Vinoth Kumar, B Sivaraman; Supervision: P Ganesan, L Vinoth Kumar, B Sivaraman.

AI USE DECLARATION

During the preparation of this work, the authors used ChatGPT (OpenAI) for grammar correction and language editing. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on a reasonable request from the corresponding author.

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