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Fermented *Sargassum*-Based Seafood Rice Seasoning: Prototype Development and Mix Design Optimization



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Abstract.

Direct incorporation of brown-seaweed biomass into foods is limited by its fibrous texture and by the challenge of retaining desirable marine and umami notes without an excessive fishy odor. This study evaluated whether fermented commercial *Sargassum* spp. biomass could be incorporated into a dry seafood seasoning for rice and whether a constrained mix design could identify a formulation with high preliminary hedonic acceptability.

Commercial dried *Sargassum* spp. biomass was rehydrated for 6 h, washed, pretreated with 1.5% sodium bicarbonate at 90–100°C for 2 h, reduced to 1–2-mm fragments, and fermented with a mixed lactic starter containing *Companilactobacillus farciminis* and *Lactiplantibacillus pentosus*. The fermentation involving 2.15% starter culture and 5.0% sugar lasted for 86 h at 30°C. The methods of hot-air, low-temperature, and freeze drying were compared using moisture content and handling attributes. Seven variable ingredients were optimized within predefined ranges in an 18-run constrained mix design comprising 15 unique formulations. The response was the mean overall hedonic score for each run, based on evaluations by 30 assessors on a nine-point scale.

The fermented biomass had a pH of 4.56 ± 0.05 . The freeze-drying processing at $-50 \pm 2^\circ\text{C}$ for 40 h yielded material with $4.51 \pm 0.20\%$ moisture and a crisp, loose, non-clumped structure. It was selected on the basis of handling properties. The drying routes were not compared by nutrient or volatile retention. The first-order mix model was significant ($F = 45.40$, $p < 0.001$, $R^2 = 96.12\%$, adjusted $R^2 = 94.00\%$). The selected formulation comprised 30% fermented seaweed biomass, 10% *Porphyra/Pyropia*-type dried red seaweed, 10% dried tuna, 5% dried shrimp, 25% roasted sesame, 10% mung bean, 5% carrot, 3% sugar, and 2% sodium chloride. The observed acceptability score was 8.30 ± 0.54 versus a predicted score of 8.43. The final product contained $4.64 \pm 0.30\%$ moisture, $28.50 \pm 1.58\%$ protein, $15.30 \pm 0.32\%$ total ash, and $15.00 \pm 0.64\%$ lipid on an as-received basis.

The sequential combination of fermentation, drying-route selection, and constrained mix optimization demonstrated the feasibility of the tested prototype and identified a formulation for independent confirmation. Because the selected solution lay on several formulation bounds, it represents the most favorable region within the tested domain rather than a universal optimum. The evidence was limited to preliminary hedonic testing and did not establish nutrient retention, shelf-life stability, comprehensive food safety, health effects, or market-level acceptance.

Keywords. Acidification, hedonic acceptability, *Sargassum* spp. biomass, drying, fermentation, formulation, mix design, pseudo-components, rice seasoning, valorization

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Приправа для риса на основе ферментированных водорослей (*Sargassum* spp.): разработка рецептуры и оптимизация компонентного состава



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Аннотация.

Волокнистая текстура бурых водорослей осложняет их прямое включение в рецептуру пищевых продуктов. Кроме того, сложно сохранить желаемые морские ноты и вкус умами без появления избыточного рыбного запаха. В данном исследовании оценивали возможность включения ферментированной биомассы водорослей *Sargassum* spp. в состав сухой приправы для риса, а также возможность применения метода планирования эксперимента с ограничениями для определения компонентного состава с высокой предварительной потребительской приемлемостью.

Сухую биомассу морских водорослей (*Sargassum* spp.) регидратировали в течение 6 ч, промывали и обрабатывали 1,5 % раствором бикарбоната натрия при температуре 90–100 °С в течение 2 ч. Затем сырье измельчали до размера частиц 1–2 мм и ферментировали смешанной молочнокислой закваской (*Companilactobacillus farciminis*, *Lactiplantibacillus pentosus*). Процесс проводили при температуре 30 °С в течение 86 ч с внесением 2,15 % закваски и 5 % сахара. Методы конвективной, низкотемпературной и сублимационной сушки сравнивали по содержанию влаги и технологическим свойствам полученного продукта. Эксперимент с ограничениями по получению оптимального компонентного состава включал 18 опытов и 15 уникальных рецептов; в пределах заданных диапазонов оптимизировали соотношение семи переменных ингредиентов. Среднюю гедонистическую оценку для каждого варианта определяли на основе данных, полученных от 30 дегустаторов (9-балльная шкала).

Ферментированная биомасса характеризовалась рН $4,56 \pm 0,05$. Материал, полученный методом сублимационной сушки при -50 ± 2 °С в течение 40 ч, имел хрустящую, рыхлую, рассыпчатую структуру и содержание влаги $4,51 \pm 0,20$ %. Его выбрали из-за продемонстрированных при обработке свойств. Способы сушки не сравнивались по сохранению питательных или летучих веществ. Модель смеси первого порядка оказалась значимой ($F = 45,40$, $p < 0,001$, $R^2 = 96,12$ %, скорректированный $R^2 = 94,00$ %). Оптимальная рецептура включала 30 % ферментированной биомассы морских водорослей, 10 % сушеных красных морских водорослей *Porphyra/Pyropia*, 10 % сушеного тунца, 5 % сушеных креветок, 25 % жареного кунжута, 10 % маша (бобы мунг), 5 % моркови, 3 % сахара и 2 % хлорида натрия. Наблюдаемая оценка приемлемости составила $8,30 \pm 0,54$, тогда как прогнозируемая оценка – 8,43. Полученный продукт в исходном состоянии содержал $4,64 \pm 0,30$ % влаги, $28,50 \pm 1,58$ % белка, $15,30 \pm 0,32$ % золы и $15,00 \pm 0,64$ % липидов.

Последовательное сочетание ферментации, выбора способа сушки и оптимизации рецептурного состава методом планирования эксперимента с ограничениями доказало перспективность тестируемого прототипа и позволило определить рецептуру для независимого подтверждения результатов. Поскольку выбранный вариант оказался на стыке нескольких установленных ограничений, он представляет собой наиболее оптимальную зону в рамках исследованных параметров, а не абсолютный оптимум. Полученные данные ограничены предварительными гедонистическими тестами и не позволяли оценить сохранение питательных веществ, стабильность при хранении, полную безопасность продукта, его влияние на здоровье и востребованность на рынке.

Ключевые слова. Закисление, гедонистическая приемлемость, биомасса *Sargassum* spp., сушка, ферментация, рецептура, проектирование смеси, псевдокомпоненты, приправа для риса, повышение ценности продукта

Финансирование. Исследование подготовлено в рамках пилотного проекта по применению биотехнологий для производства продуктов с добавленной стоимостью из морских водорослей.

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Introduction

Rice seasonings, such as Japanese furikake, are dry, portionable products used to add flavor and texture to rice and other ready-to-eat foods. Seaweed, sesame, and dried seafood are established ingredient classes in furikake-type formulations, and recent work confirms their continued relevance to seasoning development [1].

Seaweeds contribute minerals, dietary fiber, polysaccharides, and characteristic marine flavors to food products. Moderate marine and umami notes may enhance product identity, whereas pronounced fishy odor can reduce acceptance. Product development therefore requires control of both the physical form of seaweed and its sensory intensity rather than simply maximizing its proportion. Commercial *Sargassum* biomass varies with species composition, harvest conditions, and postharvest handling. As a result, conclusions should be restricted to the tested biomass and processing window rather than generalized across the genus [2, 3]. In Vietnam, commercial *Sargassum* biomass is locally available, but its direct use in formulated convenience seasonings remains less developed than extraction-based applications.

Fermentation was used to acidify the biomass and improve its suitability for subsequent drying and blending. Lactic fermentation is a popular processing method for macroalgal substrates, although its effects vary with the seaweed, microbial culture, and processing conditions [4–6]. A mixed culture of *Companilactobacillus farciminis* and *Lactiplantibacillus pentosus* served as the lactic starter. Starter cultures were not compared, and volatile compounds were not quantified. Accordingly, the study did not attribute aroma modification to a strain-specific biochemical mechanism.

The study integrated fermented *Sargassum*-based biomass with drying-route selection and constrained optimization of a seven-component seasoning mix. This linkage matters because a drying process may achieve low moisture yet yield a hard or clumped ingredient that disperses poorly in a dry seasoning. Mix design is a well-established protocol, which was applied here to a defined product-development problem within explicit ingredient bounds. Specifically, the research characterized the fermented biomass, selected the optimal drying route based on moisture and handling properties, optimized the seasoning formulation, compared the predicted and the observed acceptability for the selected formulation, and determined its proximate composition. The study did not evaluate health effects, market-level consumer acceptance, shelf life, or comprehensive product safety.

Study objects and methods

Raw materials. Commercial dried *Sargassum* spp. biomass was obtained from the Nha Trang coastal area, Vietnam, in sun-dried, bagged form. The procurement year, supplier specification, and species-level voucher information were unavailable. Accordingly, the raw material was reported at genus level as commercial *Sargassum*

spp. biomass. Other formulation ingredients included dried tuna flakes, dried shrimp fragments, commercial *Porphyra/Pyropia*-type dried red seaweed, roasted sesame, mung bean, carrot, sugar, and sodium chloride.

Preparing and fermenting *Sargassum*-based biomass. Dried biomass was rehydrated in water for 6 h, washed, pretreated in 1.5% sodium bicarbonate solution at 90–100°C for 2 h, and washed again before being reduced to 1–2-mm fragments for fermentation. We did not record the liquid-to-solid ratio during rehydration and the total wash-water volume.

The experiment included mixed lactic starter containing *Companilactobacillus farciminis* (formerly *Lactobacillus farciminis*) and *Lactiplantibacillus pentosus* (formerly *L. pentosus*). The current genus names follow the taxonomy specified in [7]. The culture was selected as a food-compatible starter for acidification rather than through a strain-screening experiment. No source and lot information for the starter and principal reagents was available.

The fermentation was conducted with 2.15% starter culture and 5.0% sugar at 30°C for 86 h. These parameters served as fixed operating set points rather than optimization ranges. The fermented biomass was then pressed to remove liquid. Supplementary Table S1 summarizes the processing and drying conditions. Figure 1 shows the overall workflow.

Comparing drying methods. The pressed fermented biomass was dried by one of three routes: hot-air drying at $60 \pm 2^\circ\text{C}$ for 10 h with a material thickness of 2–3 cm; low-temperature drying at $20 \pm 2^\circ\text{C}$ for 36 h with a similar thickness; freeze drying at $-50 \pm 2^\circ\text{C}$ for 40 h. The drying-equipment identity and detailed freeze-dryer pressure and temperature profiles were not recorded. After drying, the biomass was size-reduced and sifted through a 2-mm sieve.

The drying routes were compared using moisture content and handling attributes (color, texture, aroma, looseness, and clumping). These attributes were chosen to identify a dry ingredient suitable for uniform dispersion in a particulate seasoning. Although drying can alter seaweed structure and composition, nutrient and volatile retention were not measured [8–10]. The selection therefore reflects handling performance rather than superior nutrient or aroma preservation.

Formulation design and mix optimization. The formulation was developed in Statgraphics XV using a constrained mix design. The seven variable ingredients included fermented seaweed biomass (X_1), *Porphyra/Pyropia*-type dried red seaweed (X_2), dried tuna (X_3), dried shrimp (X_4), roasted sesame (X_5), mung beans (X_6), and carrots (X_7). Sugar and sodium chloride were fixed at 3% and 2%, respectively; the seven variable ingredients accounted for the remaining 95%.

The working ranges were 30–35% fermented seaweed biomass, 10–15% red seaweed, 10–15% dried tuna, 5–10% dried shrimp, 20–25% roasted sesame, 10–15%

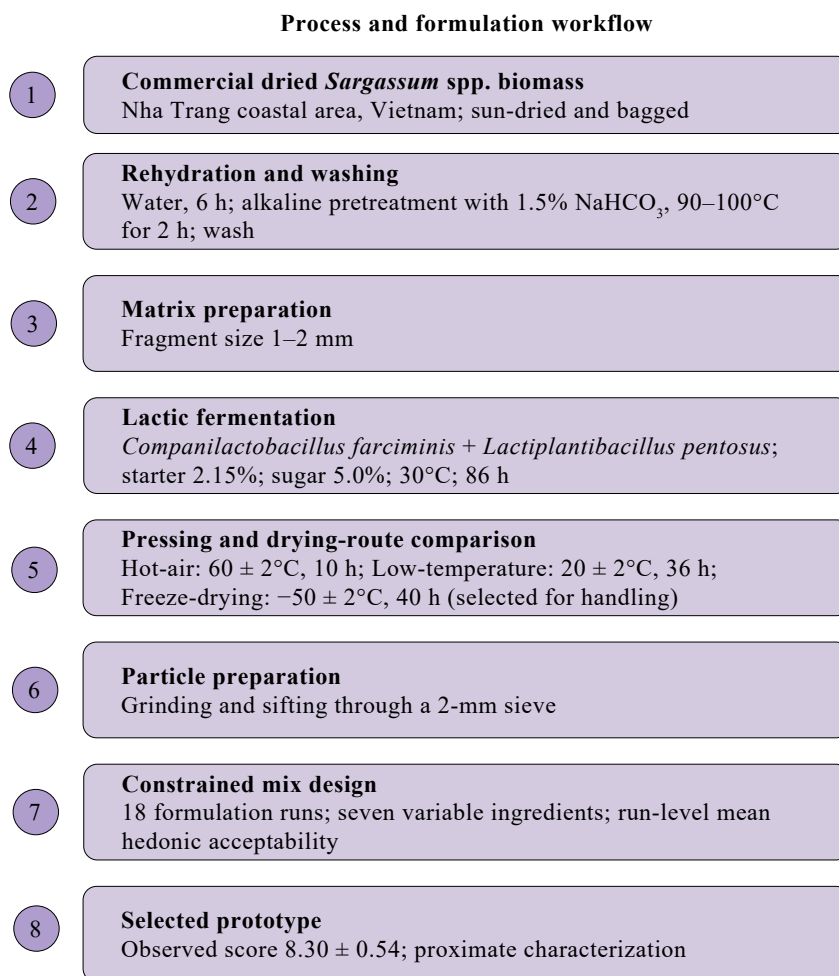


Figure 1. Process workflow for preparing fermented *Sargassum*-based biomass and developing a seafood rice-seasoning prototype, including the fixed fermentation conditions

Рисунок 1. Технология подготовки ферментированной биомассы бурых морских водорослей (*Sargassum* spp.) и разработки рецептуры приправы для риса (с фиксированными условиями ферментации)

mung beans, and 5–10% carrots. The overall hedonic acceptability was the response variable. The 18 runs comprised 15 unique ingredient combinations because three formulations were repeated in the analyzed design matrix. The pseudo-components were calculated as $Z_i = (X_i - \text{lower bound})/5$ for each 5-percentage-point working range. Supplementary Table S3 provides the complete matrix and pseudo-components. The approach followed established mix experiment principles [11–12] and their application to food formulation [13].

A first-order linear mix model was fitted to the run-level mean scores. The model fit was assessed using analysis of variance (ANOVA), R^2 , adjusted R^2 , predicted values, and residual diagnostics. The standardized-residual plot included a zero line and descriptive reference lines at ± 2 , which were neither confidence intervals nor a formal outlier test. Because assessor-level observations were unavailable, the the diagnostics apply to formulation-run means rather than assessor-level variation.

Sensory acceptability test. Thirty assessors familiar with rice-seasoning products evaluated the samples on a nine-point hedonic scale ranging from 1 (“dislike extremely”) to 9 (“like extremely”). The assessors were informed that the samples contained seaweed, seafood ingredients, sesame, and mung beans. The mean overall acceptability score for each formulation run was used in the mix model. Because assessor-level raw scores were unavailable, the sensory analysis was limited to preliminary formulation-level acceptability and was not interpreted as a representative consumer study [14, 15].

Proximate composition analyses. The contents of moisture, proteins, total ash, and lipids were reported on an as-received basis unless stated otherwise. Sampling followed Vietnamese National Standard TCVN 5276:1990. The contents of proteins, moisture, ash, and lipids were determined according to Vietnamese National Standards TCVN 3705:1990, TCVN 8135:2009, TCVN 5105:2009, and TCVN 3703:2009, respectively.

Ethics statement. Participation in the preliminary sensory acceptability evaluation was voluntary. The assessors were informed about the product and its potentially allergenic ingredients, including seafood, sesame, and mung beans, and provided informed consent before evaluation. The study involved no clinical intervention, biological sampling, or collection of sensitive personal data.

Statistical analysis. The data are presented as mean $\pm$ standard deviation where available. The mix modeling and analysis of variance relied on Statgraphics XV, with descriptive calculations in Microsoft Excel. The analytical results were treated as replicated measurements only when replicate data were available. The sensory model diagnostics were based on run-level mean scores and therefore did not quantify assessor-level variability.

Results and discussion

Fermented biomass profile. The fermented biomass was brown to dark brown and soft, with a characteristic fermented-seaweed aroma, no overpowering fishy note, and a neutral to slightly sour taste. Its pH was 4.56 ± 0.05 , the moisture level was $78.54 \pm 0.12\%$, and the protein content was $1.04 \pm 0.11\%$. The pH was consistent with acidification under the tested conditions. Because matched pre-fermentation chemical and volatile measurements were not available, these endpoint values cannot quantify fermentation-induced changes in composition or aroma. Recent reviews likewise show that the effects of seaweed fermentation depend strongly on substrate and process conditions [4, 5].

The higher protein percentage after freeze drying is best interpreted in relation to water removal and the as-received reporting basis rather than protein synthesis or selective nutrient enrichment. A nutrient-retention comparison would require matched initial and final dry-matter measurements, material balances, and route-specific replicate analyses. Fermentation and drying is the process steps rather than evidence of compositional enhancement.

Selecting the drying route. The hot-air drying yielded a dark brown to nearly black, hard, nonporous,

clumped material, whereas the low-temperature drying yielded a dark-brown material that remained tough and clumped. For these two routes, the study records provided only a combined moisture range of 4.5–4.6%, without route-specific replicate values. The freeze drying yielded a brown to dark brown, crisp, loose, non-clumped material with $4.51 \pm 0.20\%$ moisture and $5.16 \pm 0.16\%$ protein. It was selected because its handling properties matched the intended particulate seasoning format (Table 1).

The comparison addressed technological handling rather than composition. Published studies show that seaweed drying routes involve trade-offs among moisture removal, structure, processing intensity, and component retention [8–10]. The present results support freeze drying for looseness and ease of mixing; comparative retention of protein, lipid, and volatile compounds was not measured.

Freeze drying also has practical disadvantages, including a longer processing cycle, as well as greater equipment and energy demands than conventional hot-air drying. Its selection here is therefore a prototype-stage handling decision rather than an economic or industrial optimum. To ensure successful scale-up, a comparison of flowability, particle-size distribution, water activity, energy demand, and sensory quality should be conducted under optimized hot-air, hybrid, or low-temperature drying conditions.

Mix model and diagnostics. The overall acceptability scores ranged from 6.1 to 8.3 across the 18 formulation runs. The first-order mix model was significant ($F = 45.40$, $p < 0.001$), with $R^2 = 96.12\%$ and adjusted $R^2 = 94.00\%$. In terms of the pseudo-components, the fitted equation was as follows:

$$Y = 6.26Z_1 + 6.86Z_2 + 8.08Z_3 + 6.47Z_4 + 8.43Z_5 + 6.95Z_6 + 6.15Z_7$$

where Y was overall acceptability and Z_1 – Z_7 were the constrained pseudo-components. The coefficients shown

Table 1. Drying-route comparison for fermented *Sargassum*-based biomass

Таблица 1. Сравнительный анализ способов сушки ферментированной биомассы морских водорослей (*Sargassum* spp.)

Drying route	Processing condition	Moisture result	Handling attributes	Decision
Hot-air drying	$60 \pm 2^\circ\text{C}$, 10 h; thickness approximately 2–3 cm	Recorded overall range: 4.5–4.6%*	Dark brown to nearly black; hard, nonporous, clumped	Not selected
Low-temperature drying	$20 \pm 2^\circ\text{C}$, 36 h; similar thickness	Recorded overall range: 4.5–4.6%*	Dark brown; seaweed odor; tough, clumped	Not selected
Freeze drying	$-50 \pm 2^\circ\text{C}$, 40 h	$4.51 \pm 0.20\%$	Brown to dark brown; crisp, loose, non-clumped	Selected

Note: * – for hot-air and low-temperature drying, the study records provided only an overall moisture range of 4.5–4.6%; route-specific replicate values were unavailable.

Примечание: * – для образцов, полученных методом конвективной и низкотемпературной сушки, имеются данные только об общем диапазоне влажности (4,5–4,6 %); отсутствуют данные параллельных определений для каждого конкретного метода.

are rounded (see Supplementary Table S3 for model-generated predicted values). The positive coefficients should not be interpreted as independent additive effects outside the constrained mix domain. Within the tested domain, roasted sesame and dried tuna had the largest fitted coefficients whereas formulations at the upper tested bounds for carrot, shrimp, or fermented biomass had lower run-level scores.

The predicted-versus-observed plot showed close agreement across the analyzed run matrix (Fig. 2a). Run 2 was the only point above the +2 descriptive reference line (standardized residual = 2.3006), and no run was below -2 . This fact was treated as a diagnostic flag rather than a formal outlier because the ± 2 lines served as descriptive references, not confidence limits, and assessor-level data were unavailable (Fig. 2b).

The high R^2 should be viewed in the context of the small, constrained design and the use of run-level mean responses. It describes the model fit within the tested

domain but does not establish predictive performance for new ingredient ranges, independent production batches, or broader consumer populations. Independent confirmation with assessor-level data would enable mixed-effects or repeated-measures analysis and a more informative assessment of prediction uncertainty.

Selected formulation and confirmation. The selected formulation contained 30% fermented seaweed biomass, 10% *Porphyra/Pyropia*-type dried red seaweed, 10% dried tuna, 5% dried shrimp, 25% roasted sesame, 10% mung bean, 5% carrot, 3% sugar, and 2% sodium chloride (Table 2). The model predicted a score of 8.43, whereas the observed score was 8.30 ± 0.54 , a difference of 0.13 scale units.

The seven variable ingredients accounted for 95% of the formulation, while sugar and sodium chloride accounted for the remaining 5%. Because the selected formulation was already one of the 18 analyzed runs, its observed score constitutes a within-design confirmation

Table 2. Mix variables, working ranges, and selected formulation

Таблица 2. Переменные компоненты в составе смеси, рабочие диапазоны и отобранная рецептура

Variable	Ingredient	Working range, %	Selected formulation, %
X_1	Fermented <i>Sargassum</i> -based biomass	30–35	30
X_2	<i>Porphyra/Pyropia</i> -type dried red seaweed	10–15	10
X_3	Dried tuna	10–15	10
X_4	Dried shrimp	5–10	5
X_5	Roasted sesame	20–25	25
X_6	Mung beans	10–15	10
X_7	Carrots	5–10	5
Fixed	Sugar	3	3
Fixed	Sodium chloride	2	2

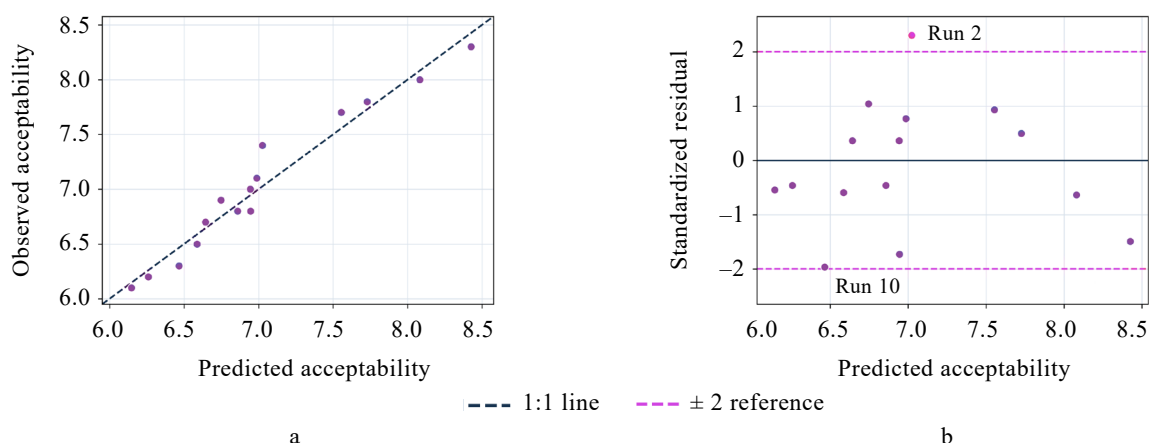


Figure 2. Model diagnostics for the 18-run formulation matrix: a – predicted versus observed run-level mean acceptability with a 1:1 line; b – standardized residuals versus predicted values with zero and ± 2 descriptive reference lines (these lines are neither confidence intervals nor a formal outlier test)

Рисунок 2. Диагностическая оценка модели для 18-точечной рецептурной матрицы: а – прогнозируемые средние значения потребительской приемлемости и экспериментальные (наблюдаемые) (линия 1:1); б – стандартизированные остатки и прогнозируемые значения (с указанием опорных линий, нулевой и ± 2). Данные линии носят описательный характер и не являются ни доверительными интервалами, ни формальным критерием для выявления аномальных значений

Table 3. Mix model and selected formulation summary

Таблица 3. Модель компонентного состава смеси и отобранная рецептура: сводная информация

Item	Reported value
Formulation runs	18 runs; 15 unique formulations; repeated formulations at runs 4/17, 12/16, and 13/18
Response	Run-level mean overall hedonic score (nine-point scale)
Model	First-order linear constrained mix model using pseudo-components
<i>F</i> -ratio; <i>p</i> -value	45.40; <i>p</i> < 0.001
<i>R</i> ² ; adjusted <i>R</i> ²	96.12%; 94.00%
Fitted equation	$Y = 6.26Z_1 + 6.86Z_2 + 8.08Z_3 + 6.47Z_4 + 8.43Z_5 + 6.95Z_6 + 6.15Z_7$
Predicted score	8.43
Observed score	8.30 ± 0.54
Diagnostics	Run-level predicted values, residuals, and standardized residuals are reported in Supplementary Table S3 and Figure 2

Table 4. Process and product-composition values

Таблица 4. Обработка и компонентный состав продукта

Sample or product stage	Parameter	Reported value*	Interpretation
Fermented biomass	pH	4.56 ± 0.05	Acidification endpoint
Fermented biomass	Moisture	78.54 ± 0.12%	Fermented biomass characterization
Fermented biomass	Proteins	1.04 ± 0.11%	Fermented biomass characterization; not a before vs. after comparison
Freeze-dried fermented biomass	Moisture	4.51 ± 0.20%	Drying endpoint
Freeze-dried fermented biomass	Proteins	5.16 ± 0.16%	Dried biomass characterization
Selected seasoning	Moisture	4.64 ± 0.30%	Prototype characterization
Selected seasoning	Proteins	28.50 ± 1.58%	Proximate composition
Selected seasoning	Total ash	15.30 ± 0.32%	Proximate composition
Selected seasoning	Lipids	15.00 ± 0.64%	Proximate composition

Note: * – as-received basis unless stated otherwise.

Примечание: * – в пересчете на исходную массу, если не указано иное.

rather than an independent validation (Table 3). The close predicted versus observed agreement supports the model-guided selection within the tested bounds but does not justify extrapolation beyond those bounds or to broader consumer populations.

The mix design was appropriate because changing the proportion of one ingredient necessarily altered the proportions of the others. The model therefore represents balance within the constrained seven-component system rather than isolated causal effects of individual ingredients, consistent with the mix design theory [11–13].

The selected formulation was at the lower bounds of six variable ingredients and the upper bound of roasted sesame. For a first-order linear mix model, a boundary optimum identifies the most favorable region within the specified domain rather than a universal optimum. Further work should explore the sesame–tuna–seaweed region around this boundary in independent production batches and test whether a quadratic Scheffé model captures a curvature that the present first-order model cannot represent.

Prototype composition, practical implications, and limitations. The selected product contained $4.64 \pm 0.30\%$

moisture, $28.50 \pm 1.58\%$ protein, $15.30 \pm 0.32\%$ total ash, and $15.00 \pm 0.64\%$ lipid on an as-received basis (Table 4). These values describe the tested prototype but do not demonstrate its nutritional superiority. Total ash reflects contributions from the marine ingredients, sesame, and added sodium chloride; the complete mineral and sodium profile was not determined. The lipid content contributes to flavor and mouthfeel but also increases the importance of oxidative stability and packaging performance during further production stages.

The study provides a defined starting formulation and process conditions for further product development. Before scale-up, independent production batches should be used to confirm the formulation and to evaluate mixing uniformity, particle segregation, water activity, microbiological quality, lipid oxidation, packaging-barrier performance, and sensory stability. Potential seaweed-associated hazards, including heavy metals, iodine, and arsenic speciation, should also be assessed because commercial *Sargassum* biomass can vary with origin and species composition [2, 3].

The particulate formulation also raises physical quality issues that were not captured by the sensory model.

Differences in particle size, density, and surface oil can promote segregation during blending, filling, transport, and storage, causing portions from the same package to differ from the laboratory blend. A prospective scale-up should therefore define mixing sequence and time, sieve fractions, target bulk density, and a sampling plan for blend uniformity. This is especially relevant because low-density dried seaweeds are combined with denser seafood and seed particles.

This research did not measure carbohydrate, dietary fiber, fatty-acid composition, nutrient retention across the drying routes, volatile compounds, and paired chemical measurements before and after fermentation. The 30-person panel supported only preliminary formulation-level acceptability, and the selected formulation was not evaluated in an independent validation batch. The current data therefore identify a promising formulation region while leaving storage stability, comprehensive safety, nutrient retention, and market-level consumer acceptance for subsequent studies.

Conclusion

Commercial *Sargassum* spp. biomass underwent a six-hour rehydration, 1.5% sodium bicarbonate pretreatment at 90–100°C for 2 h, and lactic fermentation with 2.15% starter culture and 5.0% sugar at 30°C for 86 h. The freeze drying yielded a crisp, loose, non-clumped biomass with $4.51 \pm 0.20\%$ moisture and was selected on the basis of handling properties. The drying comparison assessed neither nutrient nor volatile retention. The significant mix model ($F = 45.40$, $p < 0.001$, $R^2 = 96.12\%$) identified a boundary formulation with an observed acceptability score of 8.30 ± 0.54 , close to the predicted value of 8.43. The final product contained $4.64 \pm 0.30\%$ moisture, $28.50 \pm 1.58\%$ protein, $15.30 \pm 0.32\%$ total ash, and $15.00 \pm 0.64\%$ lipid. Together, these results support prototype feasibility within the tested process and formulation domain. Scale-up or market-level claims require independent production batches, broader consumer testing, storage studies, and comprehensive safety assessment.

Contribution

All the authors contributed equally to the study and bear equal responsibility for information published in this article.

Conflict of interest

The authors declared no conflict of interest regarding the publication of this article.

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Supplementary information

The supplementary material contains Table S1 (processing and drying conditions), Table S2 (mixture-model summary), and Table S3 (18-run formulation matrix, pseudo-components, predicted values, residuals, and standardized-residual diagnostics). The supplementary material can be found online at <https://doi.org/10.21603/2074-9414-2026-3-2660>

Data availability

The formulation matrix and run-level model-diagnostic data are provided in Supplementary Table S3. Assessor-level raw sensory data were unavailable.

Критерии авторства

Все авторы внесли равный вклад в исследование и несут равную ответственность за информацию, опубликованную в этой статье.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов в связи с публикацией данной статьи.

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Дополнительные материалы

Дополнительные материалы содержатся в Таблице S1 (условия обработки и сушки), Таблице S2 (сводная модель компонентного состава) и Таблице S3 (матрица рецептуры по результатам 18 экспериментов, псевдокомпоненты, прогнозируемые значения, остатки и диагностика стандартизированных остатков). Дополнительные материалы доступны онлайн по адресу: <https://doi.org/10.21603/2074-9414-2026-3-2660>

Доступность данных

Матрица рецептуры и данные диагностики модели на уровне экспериментов представлены в Таблице S3 (см. Дополнительные материалы). Исходные данные гедонистической оценки на уровне отдельных дегустаторов отсутствуют.

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