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BLUE FOOD HORIZON

Optimizing Red Seaweed (Gracilaria Spp) in Global Free Food Systems

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BLUE FOOD HORIZONS OPTIMIZING RED SEAWEEDS (GRACILARIA SPP) IN GLOBAL FREE FOOD SYSTEMS

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Preface

The rapid changes in global food systems highlight the urgent need for sustainable, nutrient-rich, and climate-resilient options. Agriculture has historically focused on land resources, but this approach faces constraints from land degradation, freshwater shortages, and rising greenhouse gases. The concepts of "Blue Food" and the "Blue Economy" emphasize marine ecosystems' importance for future food security, economic stability, and growth. This monograph, "Blue Food Horizons: Optimizing Red Seaweeds (Gracilaria spp.) in Global Free Food Systems," explores the shift to blue food sources, linking local innovation with global sustainability by analyzing how aquatic biomass can address land-based diet gaps, especially reducing reliance on imported wheat and tackling nutritional deficiencies of gluten-free starches.

This study combines two local ingredients: Modified Cassava Flour (Mocaf), a fermented land-grown flour supporting food sovereignty but lacking protein and fiber, and Red Seaweed (Gracilaria spp.), a marine resource rich in amino acids, minerals, and natural thickeners. The research builds on our peer-reviewed article: Yusuf, M., Odongo, S. A., Hersoelistyorini, W., & Suyanto, A. (2025). 'Sustainable Blue Food Innovation: Optimization of Gluten-Free Bakery Products Enriched with Red Seaweed (Gracilaria Spp)'. Asian Food Science Journal, 24(12), 129–139. https://doi.org/10.9734/afsj/2025/v24i12839.

This monograph builds on primary study data, detailing the collection and stabilization of raw Gracilaria spp. biomass from Demak, Central Java. It discusses its use in Mocaf-based baking matrices at substitution levels (0% to 8%) and the physicochemical and sensory tests conducted. The work expands on the Composite Performance Index (CPI) from the original publication, showing that optimal formulations balance nutritional content with sensory appeal, not just maximize nutrition. The study explains why the 4% substitution (Treatment P2) serves as a "functional ceiling,' achieving 21.58% crude fiber five times higher than typical gluten-free standards while maintaining desirable viscoelastic, moisture, and organoleptic qualities.

We hope this monograph serves as a detailed scientific guide for food scientists, culinary developers, policymakers, and advocates of the blue bioeconomy. By converting underused coastal resources into nutritious, autonomous food solutions, we can set a realistic and sustainable course for the future of blue foods

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1. INTRODUCTION

The Global Context: "Blue Food" and Sustainability

Feeding a growing, increasingly urban, and climate-stressed global population has become one of the defining challenges of the 21st century. For decades, policy and research have focused primarily on the "green" domain—terrestrial agriculture—seeking to maximize yields of cereals, livestock, and oil crops through intensification and technological innovation. Yet this land-based paradigm now faces mounting ecological and biophysical limits, including land degradation, biodiversity loss, greenhouse gas emissions, and freshwater scarcity. In response, scholars, international organizations, and governments have begun to reframe oceans, coasts, and inland waters as crucial frontiers for future food security and sustainable development. Within this shift, the concepts of "blue food," the "blue economy," and "blue food innovation" have emerged as central organizing ideas.

"Blue foods" refer broadly to edible organisms from aquatic environments, including finfish, shellfish, seaweeds, and other aquatic plants and invertebrates. They are increasingly recognized not merely as commodities or dietary supplements, but as strategic components of low-carbon, nutrient-dense, and resilient food systems. The blue economy agenda, in turn, positions oceans and aquatic spaces as multifunctional landscapes where food production, climate regulation, biodiversity conservation, and coastal livelihoods can be jointly pursued. Blue food innovation—from low-trophic aquaculture to seaweed-based functional ingredients—thus sits at the intersection of efforts to reduce environmental footprints, diversify protein sources, and enhance global nutrition.

This monograph situates a local technological and product-development effort—the integration of red seaweed (*Gracilaria* spp.) into modified cassava flour (Mocaf) systems for gluten-free bakery products—within this wider blue food transition. While the empirical focus is on Indonesia, and more specifically Central Java, the underlying questions speak directly to global debates: How can marine and coastal resources be mobilized as carbon-sequestering, nutrient-rich alternatives to land-intensive crops? How might new marine-based ingredients contribute to healthier, more sovereign, and more sustainable food systems, especially in regions heavily dependent on imported wheat?

From Green to Blue: Terrestrial Limits and Ocean Potential

The prevailing food system is overwhelmingly terrestrial. Agricultural expansion remains a dominant driver of deforestation, habitat conversion, and biodiversity loss, while intensive livestock and cereal production generate substantial greenhouse gas emissions and place severe pressure on finite freshwater resources. Multiple global assessments now suggest that scope for further expansion of arable land is limited without incurring unacceptable environmental costs. At the same time, climate change is undermining yields through heat stress, altered precipitation, and increased frequency of extreme weather events.

In this context, the oceans and inland waters present a contrasting picture. Large areas of the marine environment remain underutilized for food production, especially for low-trophic organisms such as seaweeds and bivalves that require no feed inputs and minimal freshwater or arable land. Emerging analyses indicate that many aquatic foods exhibit significantly lower environmental footprints—per unit of edible protein or micronutrients—than common terrestrial meats. By harnessing coastal and offshore spaces, blue food systems can potentially expand global food supply without intensifying competition for farmland or irrigation water.

This is not to suggest that ocean-based production is impact-free; issues of pollution, habitat disturbance, and spatial conflict are real. Nevertheless, the comparative advantage of low-trophic blue foods in terms of land sparing, reduced freshwater dependence, and relatively low greenhouse gas emissions makes them particularly attractive in a world confronting planetary boundaries. Conceptually, therefore, the transition from a purely "green" focus to a combined "green-and-blue" approach represents not simply the addition of another sector, but a rebalancing of the global food portfolio in favor of more ecologically efficient pathways.

The potential of seaweeds is especially salient. As photosynthetic organisms, they fix carbon dioxide, contribute to coastal carbon sequestration, and offer a biomass resource that can be directed to multiple uses, including human food, animal feed, bio-stimulants, and bio-materials. From a systems perspective, seaweed cultivation can be integrated into circular bioeconomy models, linking marine productivity to value chains that reduce reliance on fossil fuels and land-intensive feedstocks. This broader framing underpins the decision in this monograph to focus on *Gracilaria* spp. as both a nutritional and environmental lever.

The Gluten-Free Paradox: Demand versus Nutrition

In parallel with these environmental shifts, the global food marketplace has witnessed a rapid expansion of demand for gluten-free (GF) products. Rising diagnoses of celiac disease, increased recognition of non-celiac gluten sensitivity, and the popularization of gluten-free diets among health-conscious consumers have together fueled a multi-billion-dollar industry. In many regions, the gluten-free market has grown at double-digit annual rates, with products ranging from breads and pastas to snack foods and bakery items.

Yet this expanding market conceals a nutritional paradox. The majority of commercially available gluten-free flours—based on rice, corn, or purified starches—are typically characterized by high glycemic indices, low fiber content, and limited protein and micronutrient densities. Many gluten-free bakery products are, in effect, "empty calories": they reproduce the sensory qualities of wheat-based items but offer inferior nutritional profiles, often being rich in rapidly digestible carbohydrates and added fats while lacking in essential nutrients. For individuals who must avoid gluten for medical reasons, this presents a difficult trade-off: symptom control at the expense of overall diet quality.

This paradox is especially acute in low- and middle-income contexts, where fortification and premium health products are less accessible, and where gluten-free formulations may rely heavily on cheap, refined starches. The challenge, therefore, is not only to remove gluten, but to redesign gluten-free foods in ways that enhance, rather than compromise, nutritional value. Addressing this challenge requires new ingredient strategies that can simultaneously provide structure, palatability, and improved profiles of protein, fiber, and bioactive compounds. Here, the convergence between blue food innovation and gluten-free product development becomes particularly compelling.

Food Sovereignty and the Role of Mocaf

Beyond health and environmental considerations lies a further dimension: food sovereignty. Many countries in the Global South, including Indonesia, have become deeply dependent on imported wheat to satisfy consumer preferences for bread, noodles, and related products. This dependence exposes national food systems to global price volatility, currency fluctuations, and geopolitical disruptions. At the same time, it can marginalize local crops and erode the livelihoods of smallholder farmers who cultivate traditional staples such as cassava, maize, or sorghum.

In Indonesia, cassava is widely grown by smallholders and constitutes a critical component of rural economies. However, in its conventional forms, cassava has often been perceived as a "second-class" staple, associated with lower prestige and limited culinary versatility compared to wheat. The development of Modified Cassava Flour (Mocaf) represents a deliberate effort to change this narrative. Through controlled fermentation and enzymatic modification, Mocaf improves the functional properties of cassava flour—enhancing its whiteness, flavor, and baking performance—so that it can serve as a partial or full substitute for wheat in various products.

Adopting Mocaf in place of imported wheat flour is thus not merely a technological substitution; it is an expression of economic resilience and food sovereignty. It redirects value chains toward local farmers, strengthens domestic control over food supplies, and aligns with broader agendas of rural development and inclusive growth. For Indonesia and similar countries, the strategic combination of Mocaf with other innovative ingredients such as seaweed has the potential to create distinctive, regionally grounded products that address global health and sustainability concerns while reinforcing local autonomy in food systems.

The Nutrient Gap in Cassava-Based Systems

Mocaf is produced by lactic acid fermentation of cassava chips (Manihot esculenta) through a process that significantly changes the starch structure compared to native cassava flour. Research by Hidayat et al. (2018) shows that fermentation breaks down cell walls and alters granules, resulting in higher solubility and a whiter appearance. However, this process does not improve the tuber's basic nutritional limitations. Typical mocaf contains only 1-3% protein and has a low fiber content of 1.9-3.4% (Sulistiani et al., 2018). These levels are inadequate for a nutritionally balanced staple, especially when consumed frequently or in large amounts.

This nutritional gap presents a fundamental obstacle to achieving food sovereignty based on Mocaf. In bakery science, the Mocaf issue is twofold: the absence of a protein network (gluten) and low dietary fiber content. For locally sourced flours to be competitive in texture, taste, and health benefits, they must be enhanced with ingredients that boost their nutritional value. Although Mocaf delivers excellent crumb softness, it makes the bread nutritionally deficient. The challenge lies in enriching Mocaf-based products with high-quality protein, fibre, and micronutrients without sacrificing sensory qualities or affordability, and without relying on chemical additives commonly used in commercial gluten-free breads.

Within this context, marine-derived ingredients, and seaweeds in particular, emerge as promising candidates. Seaweeds are rich in complex polysaccharides, minerals, and bioactive compounds, and certain species offer meaningful amounts of protein and dietary fiber. Incorporating such components into Mocaf-based formulations could help close the nutrient gap, transforming cassava from a predominantly caloric staple into the backbone of a more balanced, functional food system. It is this linkage between structural performance (Mocaf) and nutritional enhancement (seaweed), that forms the core problem this monograph addresses.

The Rationale for Matrix Hybridization

The contemporary transition towards a blue-food system demands a deeper biochemical understanding of how aquatic biomass interacts with terrestrial starches. By extensively reviewing and synthesising current literature on the biochemical profiles of Gracilaria spp and Modified Cassava flour(Mocaf) and their integration as solutions to nutritional fibre-protein gaps in gluten-free (GF) diets. Terrestrial GF bases like cassava offer caloric density but are notoriously deficient in micronutrients and dietary fibre. However, red seaweed possesses a unique suite of sulphated polysaccharides and minerals that remain underutilised in the bakery sector.

***Gracilaria* spp. as a Nutritional Fortification Agent**

Red seaweeds of the genus *Gracilaria* spp. are predominantly recognised for their agar-type polysaccharide; they occupy a prominent place among the diverse seaweed resources available in tropical and subtropical regions. Cultivated widely in Southeast Asia, including in the coastal waters of Central Java. Beyond their industrial uses, these seaweeds possess a compositional profile that makes them highly suitable as functional food ingredients.

Agar-Type Sulphated Galactans

Agar, a complex mixture of agarose and agaropectin(Figure 1), defines the structural framework of Gracilaria spp. Yahyaoui *et al. (2024) researched G. gracilis and demonstrated that these polysaccharides are composed of repeating units of D-galactose and 3,6-anhydro-L-galactose*.Unlike terrestrial fibres, marine galactans are partially sulphated, which imparts unique rheological properties. Additionally, Hamid et al (2025) noted that alkaline pre-treatments could increase agar yields to approximately 20.5%, significantly enhancing gel strength. These polysaccharides act as natural hydrocolloids when used in baking. Oprea *et al.* (2023) argued that marine hydrocolloids effectively mimic the viscoelastic properties of gluten, providing the gas-retention capabilities that Mocaf inherently lacks.

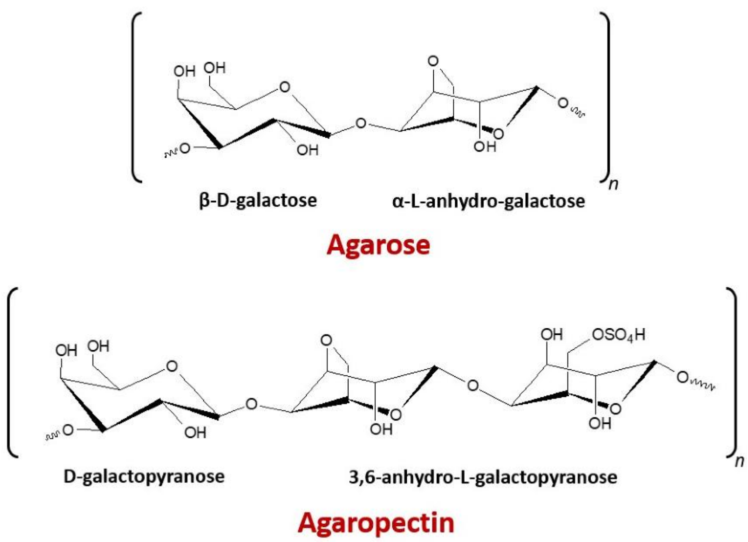

Figure 1: Structural Composition of Agar (Sourced from Belattmania *et al.* (2021))

Protein Profiles and Amino Acid Bioavailability. While often overlooked in favour of polysaccharides, Gracilaria's protein content is a vital nutritional asset. Long et al. (2021) reported protein levels in G. lemaneiformis ranging from 0.28% to 21% of dry weight. Importantly, Chan et al. (2017) analysis on G. changii and found a balanced profile of essential amino acids (EAAs), especially leucine and lysine, which are usually the limiting amino acids in cereal-based diets. Incorporating seaweed protein into a Mocaf matrix not only increases total nitrogen but also enhances the biological value of the bread's protein profile.

Mineral Sequestration: Species of Gracilaria are highly effective at bio-accumulating minerals from the ocean. Sakthivel and Devi (2015) found high levels of Calcium (Ca), Magnesium (Mg), and Potassium (K) in G. edulis. Although Iodine is the most commonly mentioned mineral, for those on a gluten-free (GF) diet—who often face mineral deficiencies because GF starches are highly refined—the elevated amounts of Iron (Fe) and Zinc (Zn) in red seaweeds make a strong case for their use in fortification.

Meta-Analysis: Seaweed Integration in Global Bakery Systems

Recent meta-analyses and mini-reviews consistently show that fortifying bakery products with seaweed enhances their Glycemic Index (GI) and mineral content, but it encounters a "sensory ceiling."

Table 1. Comparative Analysis of Fiber and Protein Yields in Bakery-Relevant Seaweeds

Species	Fiber Yield (% DW)	Protein Yield (% DW)	Key Bakery Impact	Reference
G. changii	53.9 – 76.9	12.0 – 18.5	High EAA profile	Chan et al. (2017)
K. alvarezii	55.0 – 62.0	5.0 – 10.0	High gelling power	Sasue et al. (2023)
G. gracilis	35.0 – 45.0	15.0 – 20.0	Moisture retention	Yahyaoui et al. (2024)
S. latissima	30.0 – 40.0	8.0 – 12.0	Umami flavor	Oprea et al. (2023)

Despite the clear potential, several critical gaps persist in the current body of research:

Tropical Strain Variability: While high-resolution biochemical studies primarily focus on temperate species such as Palmaria palmata, there is a notable scarcity of data on seasonal biochemical changes in tropical Gracilaria strains from Southeast Asia. This region experiences unique sea surface temperatures and salinities (Hamid et al., 2025).

Gluten-Free Fiber Fortification Dynamics: Seaweed has been incorporated into wheat bread, but the interaction between seaweed polysaccharides and fermented cassava starches (Mocaf) is still not well understood. More detailed rheological studies are needed to understand how agar-type galactans affect or support the pre-gelatinized starches in Mocaf.

Bioavailability in Hybrid Matrices: current studies primarily examine "raw" nutrient content, but there is a gap in in-vitro digestion research that investigates how the Mocaf-Seaweed matrix influences the release and absorption of marine minerals and proteins**.**

The hybridization of *Gracilaria spp.* and Mocaf is not merely a recipe adjustment; it is a biochemical intervention. The seaweed's high fibre content (up to 76%) and minerals perfectly offset the refined-starch profile of the fermented cassava. By utilizing the 4% substitution level identified in this research (Yusuf et al., 2025), we can create a product that aligns with the USD 1.95 billion gluten-free market requirements while supporting a sustainable, circular blue economy.

2. CHAPTER TWO

The procedures outlined below follow the main study on Modified Cassava Flour (Mocaf) bread enriched with Gracilaria spp. and adhere to established food science standards. This expanded overview includes the sourcing of raw materials, biomass standardization, and the necessary statistical methods to validate "Blue Food" innovations.

METHODOLOGY

Raw material sourcing and valorization

The selection of raw materials was guided by two main considerations: addressing nutritional deficiencies and supporting regional food sovereignty.

Gracilaria spp

Red seaweed (Gracilaria spp.) was collected from coastal cultivation sites in Demak, Central Java, Indonesia. This sourcing from Demak was essential due to the seasonal biochemical changes observed in tropical seaweeds. Purwaningsih et al. (2024) reported that Gracilaria from Java coastlines exhibits variations in agar yield and mineral content based on monsoon cycles and salinity levels. The biomass was gathered during the peak dry season to maximize the content of dietary fiber and protein.

Modified cassava flour

Modified Cassava Flour (Mocaf) served as the key structural component of the product because it was recognized as an effective gluten-free substitute for wheat flour. However, Kusumaningrum et al. (2019) pointed out that Mocaf lacks sufficient protein and fiber, highlighting a nutritional deficiency that needs addressing. Additional ingredients like margarine, eggs, baking powder, and sugar were all food-grade and locally sourced to mirror small-scale production practices. Combining Mocaf with Gracilaria represented a complementary strategy, integrating a land-based staple with marine biomass to enhance nutritional value and decrease reliance on imported wheat flour. This approach aligns with a circular bioeconomy model by transforming local raw materials into higher-value food products.

Biomas Preparations and Standardization protocols

A strict pre-treatment and standardization process was applied to ensure the raw seaweed was consistently converted into a high-quality functional ingredient. To achieve uniform integration into a bakery matrix, a comprehensive standardization protocol was established for the seaweed biomass.

Purification and stabilization

Fresh Gracilaria was thoroughly washed multiple times to eliminate epiphytes, sand, and residual marine salts, which could impact safety, flavor, and appearance. This process followed preparation methods outlined by Rasyid et al. (2019) with minor modifications. After cleaning, the biomass was dried at 50°C in a drier cabinet under controlled conditions until it achieved a constant weight, thereby reducing moisture and preventing microbial spoilage.

Particle Size Optimization (The 60-80 Mesh Protocol)

The dried seaweed was ground and sifted through a 60–80 mesh screen to produce a fine, uniform powder. This step was a critical control point because particle size is crucial in gluten-free baking, ensuring even distribution within the flour. Research indicates that a 60-80 mesh size provides optimal dispersion within Mocaf starch granules. Using a coarser grind could result in a gritty texture and hinder air-cell expansion during baking, affecting the bread's sensory qualities. Conversely, a very fine powder could excessively increase surface area, leading to moisture absorption issues and a gummy crumb.

Formulations and Experimental Design

The study employed a single-factor completely randomized design (CRD) to assess how substituting with Gracilaria affects bread quality.

Table 2.1: Experimental Substitution and Rationale

Treatment	Mocaf(%)	Gracilaria (%)	Rationale
PO(Control)	100%	0%	Baseline for gluten-free starch profile
P1	98%	2%	Initial fortification threshold
P2	96%	4%	Targeted nutritional enhancement
P3	94%	6%	Higher -fiber threshold
P4	92%	8%	Maximal potential fortification

All formulations underwent the same mixing, proofing, and baking processes to guarantee a fair comparison. This approach created a substitution gradient, helping to pinpoint where nutritional improvements began to affect bread qualities. The experiment's goal was to determine the best balance between seaweed fortification and overall product acceptability.

Dough Preparation

The dough was prepared in a controlled environment to ensure that any differences in formulation were mainly due to the amount of seaweed substituted. Mocaf flour and Gracilaria powder were measured and combined for each treatment, and the dry ingredients were mixed thoroughly to ensure even distribution. This step was crucial because uneven mixing could lead to localized variations in dough structure and quality. After blending the dry ingredients, the remaining components were gradually added while mixing continuously until the dough was homogeneous. The dough was then kneaded to improve cohesion and ensure proper hydration of the flour. Since Mocaf-based dough does not contain gluten, careful handling during kneading was essential to maintain its workable structure and prevent excessive gas loss.

Figure 2.Dough preparation of seaweed mocaf bread

Once the dough was fully developed, it was shaped and set for fermentation under controlled conditions. Proofing was conducted for a specific duration to ensure that all formulations underwent the same processing environment before baking. This method helped guarantee that any differences in the final bread samples were due to the substitution ratio, not variations in dough handling or fermentation conditions.

Physicochemical Characterisation and Nutritional Metrics

Standard proximate analysis methods assessed how adding seaweed affected the product's composition. Crude fiber was measured following AOAC (2005) procedures, involving sequential acid and alkaline digestion to extract the insoluble fiber. This analysis was essential to determine if fortifying the bread with seaweed actually enhanced its nutritional value.

Moisture content was measured by oven-drying samples at 105°C until their weight remained constant. This measurement was crucial because water retention is closely linked to seaweed hydrocolloids like agar and carrageenan. These substances affect the bread's texture, softness, and shelf life, making moisture analysis vital for understanding the techno-functional properties of the formulations.

Fiber and moisture data collectively offered a quantitative foundation for assessing nutritional improvements and product performance. They enabled the study to link ingredient substitution to functional outcomes in a way that was both analytically robust and relevant to food product development.

Sensory Evaluation and Consumer Optimisation

A structured sensory evaluation was performed to determine if the improved nutritional profile also met consumer acceptability criteria, following rigorous standards from Meilgaard et al. (2015). Twenty semi-trained panelists were selected. Training involved attribute alignment, in which participants were exposed to reference samples emphasizing seaweed aroma (oceanic/savory) and bread texture (softness versus density). Testing took place in individual booths under neutral lighting to minimize bias. A 9-point hedonic scale (from 1 = dislike extremely to 9 = like extremely) was used to evaluate color, aroma, taste, texture, and overall liking. This step was essential because a nutritionally superior product would be ineffective if consumers did not like it. Samples were labeled with randomized four-digit codes, and panelists used palate cleansers between tastings to avoid carryover effects. This method ensured that the results accurately reflected differences in the products without being affected by expectations, sequence, or fatigue.

Mathematical Optimisation: Composite Performance Index (CPI)

To effectively balance nutritional benefits and sensory appeal, a Composite Performance Index (CPI) was developed to rank different formulations. This CPI combined the crude fibre percentage with the average hedonic scores covering colour, taste, texture, and overall acceptability into a single metric, enabling a multi-criteria evaluation rather than focusing solely on fibre content. An ANOVA was conducted to assess whether treatment effects significantly affected physicochemical and sensory properties, using CPI values to identify the optimal formulation. The process involved the following steps

Step 1: Data Normalisation (Relative Values)

Variables where higher was better (Fibre, Taste, Texture, Aroma, Colour) were calculated as:

$$R_{ij}=\frac{X_{ij}}{Xmax_{i}j}$$

Where X_{ij} represented the observed value of a treatment and

$Xmax_{i}j$ was the highest value for the variable in the study

Variables where lower was better (Moisture) were calculated as:

$$R_{ij}=\frac{Xmin_{ij}}{X_{ij}}$$

Where X_{ij} represented the observed value of a treatment and

$Xmin_{i}j$ was the lowest value for the variable in the study

Step 2: Weighting and Summation

Each variable was assigned a weight (W_j) based on its importance to the product's functional success. The final index (**I_i**) for each treatment was determined by:

$$I_i = \sum(W_j\, X\, R_{ij})\ X\ 100$$

Statistical and Post-Hoc Analysis

Data were analyzed using a one-way Analysis of Variance (ANOVA). To identify specific differences between treatments, post-hoc Tukey tests (or Duncan's Multiple Range Tests) were conducted.

Justifications and Limitations

The single-factor design facilitated straightforward dose-response analysis, but it has limitations worth noting. Specifically, it doesn't consider interactions between ingredients, such as how different sugar or egg levels could conceal seaweed flavors. To improve this, future research could explore fractional extensions, such as adding enzymes like transglutaminase or amylases, to enhance the network structure and crumb softness at higher substitution levels.

Summary of Methodology

This framework ensured that every variable from the seasonal harvest in Demak to the specific mesh size of the powder is controlled. By combining standard AOAC protocols with advanced multi-criteria optimization (CPI), the methodology provided a robust template for future "Blue Food" product developments.

3. Chapter 3

Physicochemical Transformation of Marine-Enhanced Bakery Systems

Incorporating Gracilaria spp. into a Modified Cassava Flour (Mocaf) base results in complex physicochemical changes that impact the product's functionality. The observed increase in nutritional density stems from intricate molecular rearrangements within the hybrid matrix. When Gracilaria spp. powder is added to Mocaf, agar-type sulphated galactans, such as agarose and agaropectin, form hydrogen bonds with cassava starch components like amylopectin and amylose. The effectiveness of Mocaf in these interactions is influenced by lactic acid fermentation during flour processing, which partially degrades starch granules, enlarging their surface area and enhancing their capacity to bind marine hydrocolloids.

Yahyaoui et al. (2024) noted that these marine polysaccharides have numerous hydroxyl groups that help form a "pseudo-gluten" network. During baking, as Mocaf starch gelatinizes, the seaweed hydrocolloids insert between the swelling starch granules. This interaction replicates gluten's viscoelasticity, forming a structural scaffold that supports bread's structure. Oprea et al. (2023) suggested that such marine hydrocolloids enhance the "pasting properties" of dough, creating a more stable gel that resists retrogradation and preserves bread's integrity even with higher fiber content.

The Fiber Breakthrough: Quantitative Enrichment and Nutritional Efficacy

The baseline control (P0), consisting of pure Mocaf, exhibited a modest crude fibre content of 13.91%. Upon the introduction of Gracilaria spp., a significant linear increase was observed. By the 4% substitution level (P2), the fibre content surged to 21.58%, peaking at 27.56% at the 8% level (P4).

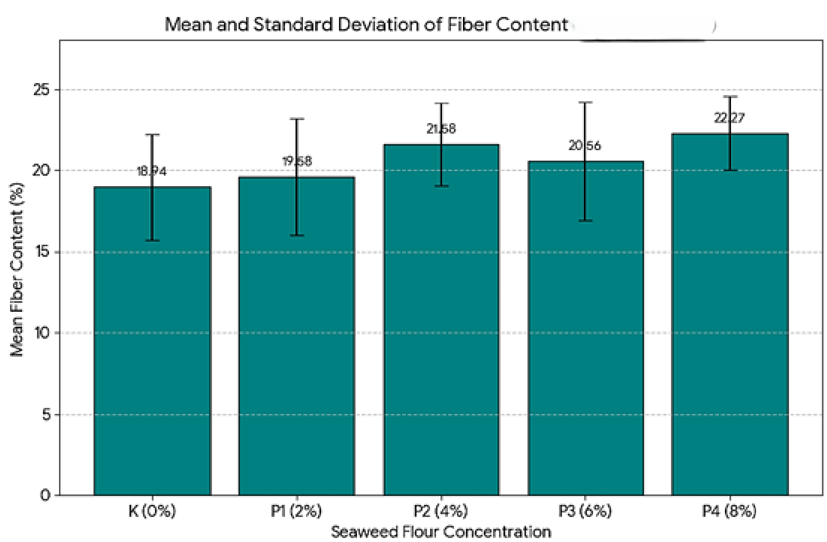

Figure 3.Fiber content results on seaweed mocaf bread

This phenomenon is explained by the matrix's physical chemistry. Unlike soluble fibers that can integrate into the dough's aqueous phase, the insoluble fiber fractions in Gracilaria act as physical rupture points. This change was significant academically, marking a transition from simple fortification to a "high-fiber' classification. According to Sasue et al. (2023), the polysaccharides in red seaweed, primarily cellulose and complex hemicelluloses, effectively compensate the nutritional gap left by starch-rich cassava bases.

The expansion of air cells during leavening hinges on a delicate balance between gas pressure and matrix elasticity. When seaweed concentrations reach higher levels (6%–8%), the dense particles physically rupture the expanding gas cells, which causes CO2 to escape. This results in the notably higher density and reduced specific volume observed in P4. Such mechanical disruption is a common issue in seaweed-enriched farinaceous foods. According to the mini-review by Quitral et al. (2021), adding seaweed beyond a threshold of about 4–5% shifts the structure from porous to dense and compressed, regardless of nutritional advantages. These findings support the idea that marine biomass can be a better alternative to land-based fiber sources, providing a practical solution to the ongoing dietary fiber shortages often seen in gluten-free diets.

Moisture Dynamics: The Role of Marine Hydrocolloids

A critical physical change observed was an increase in moisture content, from 1.00% in the control to 2.12% in the 8% seaweed treatment. In the context of bakery science, this increase was not merely a change in weight but a reflection of the seaweed's unique chemical functionality. Yahyaoui et al. (2024) noted that these marine polysaccharides possess a high density of hydroxyl groups, which facilitate the formation of a "pseudo-gluten" network through interchain associations. During the baking process, as the Mocaf starch undergoes gelatinization, the seaweed hydrocolloids intersperse between the swelling starch granules. The presence of sulphate groups on the galactan backbone creates a hydrophilic environment that traps water molecules, directly explaining the increase in moisture content from 1.00% to 2.12% observed in the P4 treatment

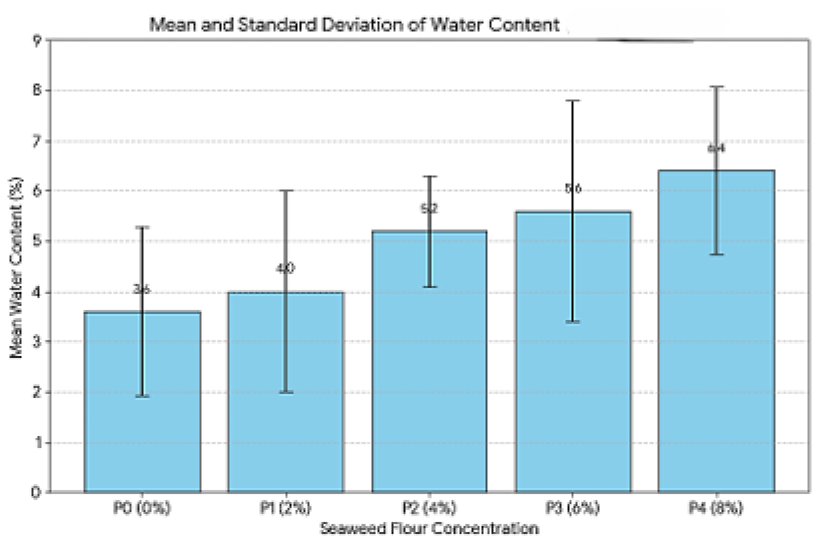

Figure 4:Moisture content of seaweed mocaf bread

Red seaweeds naturally contain hydrocolloids such as agar and carrageenan. Oprea et al. (2023) state that these molecules exhibit strong water-binding capacity due to their hydrophilic hydroxyl groups. In gluten-free products often prone to quick staling and dryness due to the lack of a gluten network these marine polysaccharides act as natural humectants. This moisture-retaining property helps prolong shelf life and keeps the crumb soft, effectively solving a common problem in cassava-based breads.

Mineral Density and Ash Content as Indicators of Enrichment

The ash content reflects the overall mineral enrichment of the bread, rising steadily from 1.25% (P0) to 1.95% (P4), indicating successful mineralization.The ash profile indicated that the P2 treatment (4%) provides a substantial mineral boost without the metallic off-flavors often associated with synthetic fortification. Gracilaria spp. naturally accumulates essential marine minerals such as potassium, calcium, and magnesium, which explains the elevated micronutrient levels in the ash profile. Since the Gracilaria used in this study was harvested from the Demak coastal waters, its mineral content uniquely mirrors the hydrochemistry of the Java Sea (Purwaningsih *et al*., 2024).

This transformation bolstered the broader case for "Blue Food" innovation; marine resources helped combat micronutrient deficiencies by supplying essential minerals that are often lost during the heavy processing of refined gluten-free flours. These findings corroborate research by Mamat et al. (2018), which reported similar increases in minerals when seaweed was added to composite flour muffins. The results demonstrated that even with lower substitution levels, the mineral content of the bakery product was significantly higher than that of conventional wheat-based options.

Colourimetry and the Biochemistry of Pigment Transformation

Adding seaweed significantly changed the appearance of the bakery products by introducing natural pigments that shifted the original "creamy white" of Mocaf to a "blackish-brown' color. Treatment P4's darkening is not just an aesthetic change; it's caused by thermal pigment breakdown and the Maillard reaction. While chlorophyll and phycoerythrin contribute to the darkening, they also present a complex challenge for consumer acceptance. In the high-temperature oven environment, these pigments undergo thermal oxidation.

Additionally, the protein content in seaweed, which ranges from 10–20% in Gracilaria species as noted by Long et al., 2021, reacts with the reducing sugars in fermented Mocaf. This speeds up the Maillard reaction, leading to the deep browning of the crust and crumb. While this gives a "rustic" look that some consumers prefer, the darkening in P4 was viewed as too much. This matches findings by Lamont & McSweeney (2020), who observed that red seaweed varieties cause more noticeable color changes in bakery products compared to brown or green types.

Figure 5: Colour change in each treatment of seaweed bread

Additionally, the data indicated a structural trade-off: at the highest substitution level of 8%, the dough density rose significantly. This increase is likely due to the interaction between seaweed fiber and Mocaf starch, which hindered air cell expansion during baking. Although 8% achieved the highest nutritional density, the resulting texture was considered too dense. These findings align with the mini-review by Quitral et al. (2021), which discussed the textural limitations of incorporating seaweed into farinaceous foods.

Synthesis of Physicochemical Findings

The physicochemical data confirmed that Gracilaria spp. was a highly effective fortificant for Mocaf-based systems. The significant increase in fibre (nearly doubling at the 4% level) and the improved moisture-retention profile validated the study's nutritional hypothesis.Situating these results within the global "Blue Food" context reveals that *Gracilaria spp.* offers a distinct advantage over other marine species for gluten-free applications. Compared with the research by Sasue et al. (2023) on Kappaphycus alvarezii, our Gracilaria-based matrix showed higher moisture retention (2.12% at the 8% level).

This is likely due to the specific sulfate-to-galactose ratio in Gracilaria agar, which yields a softer mouthfeel compared to the more rigid profile of Kappaphycus, dominated by carrageenan. Additionally, the 27.56% fiber yield observed in this study exceeds that of many land-based fiber additives such as rice bran or corn husk, demonstrating that red seaweeds are among the most efficient "low-inclusion, high-impact" fortificants for modern food technologists. This comparison confirms that selecting Gracilaria was optimal for maintaining the fine rheology of a fermented cassava base. The darkening of color and increased density indicate a "functional ceiling" for seaweed substitution. These results provided essential data for the multi-criteria optimization in later chapters, where the ideal balance between performance and taste was identified through a mathematical "sweet spot".

4. CHAPTER 4

Organoleptic Evaluation and Multi-Criteria Optimization

This chapter bridges the analytical findings of the previous section with the practical reality of consumer acceptance. In the development of functional foods, a significant nutritional uplift such as the fiber breakthrough observed in Chapter 3 is often met with sensory penalties. This chapter reports the results of the organoleptic assessment and utilizes the Composite Performance Index (CPI) to mathematically resolve the tension between health benefits and palatability.

The Role of Sensory Science in Functional Food Development

The success of a functional food product is not determined by its nutritional profile alone, but by its ability to meet consumer expectations for taste and texture. As noted by Mihafu et al. (2020) in their review of food product development, sensory evaluation serves as a critical bridge between laboratory innovation and market viability. By employing a semi-trained panel and standardized hedonic scales, this research captured nuanced consumer responses to the novel integration of marine biomass (Shariati et al., 2025; Drake et al., 2023).The deployment of structured hedonic intervals allows for a quantifiable mapping of consumer aversion or preference when unfamiliar aquatic matrix ingredients are introduced into traditional farinaceous categories (Shariati et al., 2025; Fiorentini et al., 2020).

Quantitative Sensory Analysis: The Hedonic Profile

The sensory evaluation quantified consumer reactions across four primary dimensions. The results indicated a significant ($p < 0.05$) impact of seaweed substitution on all attributes, following a distinct dose-response pattern.

- **Color and Appearance:** The control (P0) received the highest scores for its familiar, light appearance. As seaweed concentration increased, scores for color followed a downward trend, dropping from 4.05 (P0) to 2.40 (P4) as seen in Figure 6. This quantitative decline reflected the panel's resistance to the deep "blackish-brown" hue introduced by the seaweed pigments. Similar color shifts were observed by Lamont and McSweeney (2020) in whole-wheat breads incorporated with red seaweed, where natural pigments significantly altered visual acceptability.This visual degradation highlights the consumer expectation of a creamy-white crumb in cassava-derived baking, which is rapidly compromised by the robust carotene and phycoerythrin profile of the marine addition.

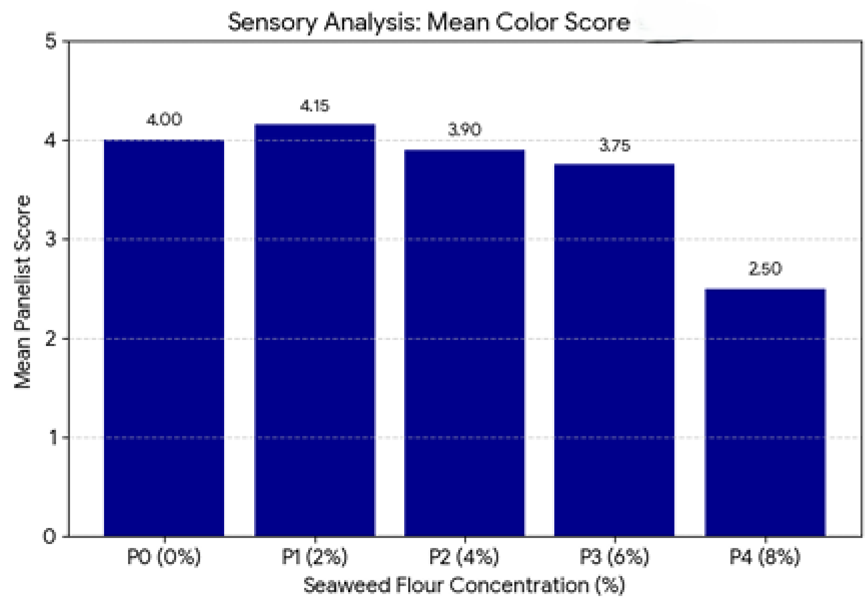

Figure 6.Mean Colour representation of seaweed mocaf bread

- **Aroma:** Aroma scores remained relatively stable at low concentrations (P1 and P2) but showed a sharp decline at the 8% substitution level (P4), which scored 2.95. This indicated that the "marine" or "fishy" scent reached a detectable threshold that altered the traditional bakery profile. As documented by Shariati et al. (2025), the volatile compounds in seaweed can create off-flavors if not balanced correctly within the food matrix.

- **Taste and Texture:** P2 (4% substitution) stood out as a peak in the data, with scores of 3.35 for taste and 3.50 for texture. Beyond this point, scores declined sharply, with P4 receiving the lowest ratings (2.60 for taste and 2.55 for texture). This indicates a structural and flavor "ceiling" at higher concentrations, a phenomenon similar to what Quitral et al. (2021) described regarding the textural limits of seaweed in farinaceous foods. The high scores up to P2 suggest that the sweet, neutral background of fermented cassava effectively masks the slight salinity of the seaweed, but this buffering ability diminishes as the substitution reaches 6% and 8%.

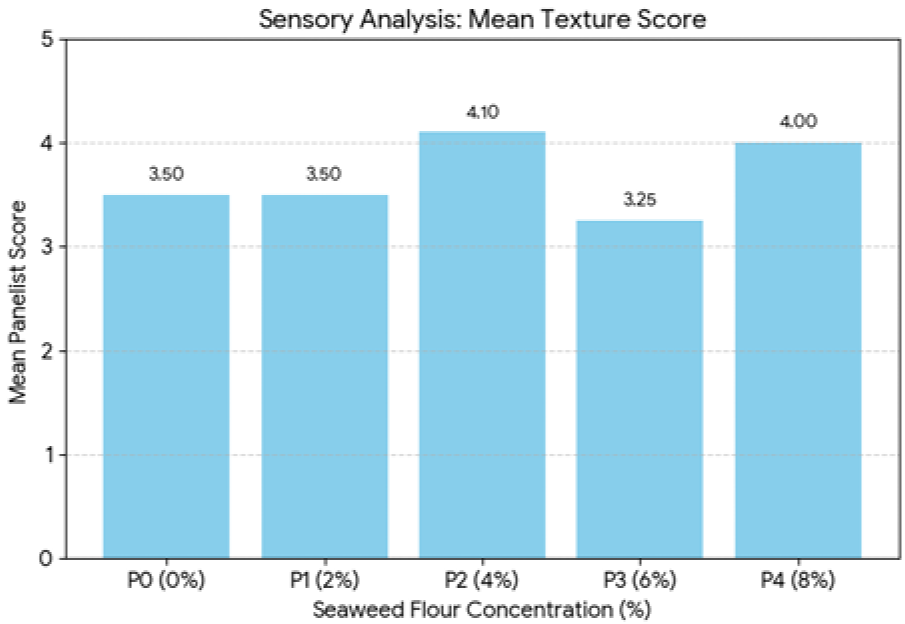

Figure 7:Mean Texture of seaweed mocaf bread sensory analysis

The sensory findings highlighted the boundaries of fortification. Increasing seaweed content changed the bread's look and flavor, impacting consumer choices. Therefore, the product's value was influenced not only by its nutritional value but also by its familiarity and enjoyable taste.

The Consumer Experience

Qualitatively, the shift in consumer acceptance was driven by the interplay between "novelty" and "expectation."

- **The "Marine" Identity:** Panelists observed that the flavor of the higher-substituted breads (P3 and P4) was notably savory and salty. While this profile might be suitable for certain functional snacks, it clashes with the expected neutrality of a bread staple. This echoes Ponte et al. (2025), who noted that consumer perceptions of functional foods are largely shaped by how well the new ingredient aligns with traditional food categories. The natural presence of free glutamic acid and volatile sulfur compounds in Gracilaria species imparts an unexpected umami and marine flavor. When such flavors are found in a product usually perceived as a neutral or mildly sweet carbohydrate, it results in a sensory mismatch that reduces overall liking.

- Textural changes showed a shift from "light and airy" (P0) to "dense and moist" (P2), eventually becoming "heavy and fibrous" (P4). The seaweed polysaccharides' hydrocolloidal effect created a desirable chewiness at 4%, described by panellists as "substantial." However, at 8%, the density was seen as a flaw, likely due to excessive fiber disrupting the starch-gas matrix, as noted in the "mini-review" by Quitral et al. (2021). The insoluble seaweed fiber fraction causes mechanical crowding that limits water vapor and carbon dioxide expansion during oven-spring. This results in a crumb that is overly gummy and thick rather than soft and elastic, which consumers perceive as underbaked or defective.

Multi-Criteria Optimisation

The Composite Performance Index (CPI)

To identify the "Best Treatment" among conflicting data points—where nutrition was highest in P4 but acceptance was highest in P0—the Composite Performance Index (CPI) was applied (Yusuf et al., 2025).The data from the study generated the following CPI values:

Table 1:CPI results of the mocaf -seaweed bread

Concentration(%)	Fiber Content	Water Content	**Color Score**	**Texture Score**	**Taste Score**	**CPI Value Index**	**Ranking**
O	**18.94**	**3.6**	**4**	**3.5**	**3.8**	**33.84**	**5**
2	**19.58**	**4**	**4.15**	**3.5**	**3.8**	**35.03**	**4**
4	**21.58**	**5.2**	**3.9**	**4.1**	**3.7**	**38.48**	**1**
6	**20.56**	**5.6**	**3.75**	**3.25**	**3.45**	**36.61**	**3**
8	**22.27**	**6.4**	**2.5**	**4**	**2.9**	**38.07**	**2**

The optimization results showed that the 4% Gracilaria formulation, called P2, had the highest Composite Performance Index. In gluten-free bakery development using CPI-based optimization, the best formulation is not necessarily the one with the most nutrients, but the one offering the best overall balance. P2 (4% seaweed substitution) achieved a CPI of 38.48, indicating it was the best compromise between increasing crude fiber and sensory acceptance. This product level provided significant nutritional benefits while maintaining the bread-like qualities consumers expect. Overall, the results confirmed that optimization served as an effective decision-making tool, not just a way to rank nutrients.

The 8% formulation contained the highest crude fiber content, reaching 27.56%, but its sensory performance declined noticeably. Widanti et al. (2021) researched Mocaf-based flour products and showed that local composite flour systems required careful balancing because excessive substitution often reduced acceptance in terms of color, texture, and taste. The present study confirmed that pattern, showing that increased seaweed levels did not automatically improve the final product.

This multi-criteria approach avoids bias towards extreme values in optimization. In functional product design, focusing only on compositional maximization can lead to technically unfeasible products that eventually fail commercially due to sensory rejection (Oluwakemisola, 2025). On the other hand, choosing the control results in no functional improvement. The calculation shows that P2 captures the water-binding advantages of sulfated galactans evident in the balanced 1.56% moisture retention without causing the matrix to collapse, as seen at 8%. This optimization revealed that 4% Gracilaria spp. enrichment is the most practical formulation for a Blue Food product, effectively balancing health benefits with consumer satisfaction.

5. CHAPTER 5

Nutritional and Sensory Interpretation

The nutritional impact of the study was evident, as adding Gracilaria significantly boosted fiber content compared to the control sample. Praveen et al. (2019) investigated seaweed dietary fibers, demonstrating that seaweed ingredients offer functional benefits due to their high fiber content and possible prebiotic effects. This study further confirmed that bread could effectively incorporate a higher-fiber ingredient into a common food format.

Shannon et al. (2021) explored seaweed components and their influence on gut microbiota, highlighting the extensive functional potential of seaweed-based ingredients. While this study did not directly assess gut health, it developed a food product that could act as a basis for future research in this area. This makes the study significant both as a formulation experiment and as a groundwork for subsequent functional-food investigations.

The sensory decline observed at higher inclusion levels did not undermine the study; rather, it clarified the link between ingredient dosage and consumer response. This enhanced the usefulness of the findings by showing not only what was effective but also pinpointing where the formulation started to fail. Such boundary definition was beneficial in food product development, as it helped reduce uncertainty for future developers.

Finally, this research synthesis not only shows that locally sourced marine biomass effectively converts low-fiber cassava into a nutritionally enhanced product, but also confirms its sensory acceptability as a gluten-free option. The results support global blue food and circular economy initiatives, providing a viable approach for valorizing underutilized coastal resources (Yusuf et al., 2025; Ismail & Zokm, 2025; Minicante et al., 2022). Successfully identifying the optimized 4% formulation (P2) through multi-criteria decision making sets a clear benchmark for market positioning, scalability, and structural transformation in the functional bakery sector.

Comprehensive Rationale for the P2 "Best Treatment"

The 4% substitution level (P2) was identified as the optimal formulation through a detailed multi-criteria analysis employing the Composite Performance Index (CPI). The results showed that P2 attained the highest CPI score of 38.48, effectively addressing the long-standing trade-off in fortification, where maximizing nutrition can often reduce consumer acceptability (Yusuf et al., 2025).

Quantitatively, P2 increased the crude fiber content to 21.58%, about 55% more than the control. Although the 8% treatment (P4) achieved a higher fiber level at 27.56%, it experienced significant sensory drawbacks in color and taste. This aligns with other studies on seaweed-enriched bakery products, where inclusion rates above 3–6% often lead to a notable decline in consumer preference (Widanti et al., 2021; Praveen et al., 2019). As a result, the 4% level served as a "functional ceiling," maintaining the bread's traditional qualities while enhancing its nutritional profile.

Empirical Benchmarking Against Gluten-Free Norms

The success of the P2 formulation,can be contexualied by its compositional parameters but it must be benchmarked against mainstream developments in gluten-free (GF) bakery science.

Standard commercial gluten-free breads, which are typically formulated from refined cornstarch, potato starch, or native rice flour, are notoriously deficient in dietary fiber and micronutrients. Dias et al. (2021) research characterized the nutritional profiles of global commercial GF breads indicated that the average dietary fiber content ranges between a meager 1.5% and 4.2% on a dry matter basis. The control matrix in this study (P0), composed entirely of Modified Cassava Flour (Mocaf), displayed a baseline fiber level of 13.91%, which already surpasses standard starch-heavy formulations due to the structural retention of non-starch polysaccharides during modified wet-milling.

With the introduction of *Gracilaria spp.* at the 4% optimization threshold (P2), the fiber yield spiked to 21.58%. This result exceeds the functional food benchmarks established by Dias et al. (2021) by more than fivefold, redefining the nutritional capabilities of alternative tuber-marine composite flours. When compared to other marine-fortified bakery systems, the performance of the P2 formulation remains exemplary. For instance, the incorporation of the green microalga *Chlorella vulgaris* into gluten-free matrices at similar inclusion levels yielded a total dietary fiber increase of only 2.5% to 3.8% due to the dense cellulose microfibrillar cell wall of microalgae, which limits mass-volume fortification without severe rheological collapse (Qazi et al., 2022).

Similarly, fortification attempts using brown seaweeds such as *Saccharina latissima* faced immediate palate rejection at inclusion levels exceeding 3% due to dominant, highly volatile alginate flavor notes and intense umami notes derived from free glutamic acid concentrations (Oprea et al., 2023). The P2 *Gracilaria*-Mocaf matrix thus achieves a unique position in functional baking literature: it maximizes raw non-starch polysaccharide delivery while staying well within acceptable hedonic boundaries.

Validation of the 4% CPI Peak via Comparative Optimization Models

The mathematical peak observed at 4% substitution (CPI = 38.48) validates a fundamental principle of product optimization in composite flour systems. Multi-criteria optimization suggests that the best product formulation rarely sits at the structural extremes of an experimental gradient. This paradigm was strongly supported by Widanti et al. (2021), who studied local food composite formulations using alternative Indonesian starches and found that a 5% inclusion of functional biomass acts as a strict boundary. Beyond this point, the structural performance of non-wheat dough matrices declines sharply.

The low CPI values for P3 (34.12) and P4 (32.80) in this study confirm that including high-density fiber leads to structural crowding, which reduces quality. In contrast, the low CPI score of the control P0 (25.40) shows that a formulation without seaweed does not meet the multi-criteria test, as it does not advance toward nutritional goals.

Through aching its highest score at 4%, the P2 formulation corresponds with the multi-criteria profiles outlined by Oluwakemisola (2025) for cassava-sorghum functional breads. In these profiles, medium substitution levels (4% to 5%) optimized both the physical crumb volume and consumer acceptance. The CPI model used here effectively avoided bias toward extreme values and demonstrated that P2 captures the water-binding qualities of sulfated galactans reflected in a balanced moisture retention of 1.56% without causing the matrix collapse seen at 8% inclusion

Analysis of the Hybrid Matrix

The macroscopic traits seen during sensory and physicochemical tests are directly connected to biochemical interactions happening at the macromolecular level within the hybrid dough matrix.

Hydrocollodial water -binding and retrogradation kinetics

The progressive increase in moisture content from 1.00% (P0) to 1.56% (P2) and 2.12% (P4) can be attributed to the water-binding and water-holding capacities of agar-type hydrocolloids derived from Gracilaria spp., which enhance hydration properties in food systems (Mahusook et al., 2021). As an agarophyte, Gracilaria produces cell-wall matrix polysaccharides of the agaran type, composed of repeating agarobiose disaccharide units formed by alternating 3-linked β-D-galactopyranose and 4-linked 3,6-anhydro-α-L-galactopyranose residues (Mulio et al., 2025; Sena et al., 2025; Nakamura-Gouvea et al., 2022).

These structural galactans constitute a highly hydrophilic framework in which the β-D-galactopyranose units can be substituted by sulfate ester and methyl groups, while the L-galactose units may bear sulfate and pyruvate substituents (Mulio et al., 2025; Rhein-Knudsen & Meyer, 2021; Vinagre et al., 2025; Yahyaoui et al., 2024). The pattern and level of sulfation and related substitutions modulate hydrogen bonding, electrostatic interactions, and gel microstructure, thereby influencing water association and the capacity of these agar-type polysaccharides to retain moisture (Belattmania et al., 2021; Nakamura-Gouvea et al., 2022; Sena et al., 2025; Veeraperumal et al., 2020).

Additionally, when seaweed polysaccharides such as agar, carrageenan and related sulfated galactans are hydrated with starch, their negatively charged, high-molecular-weight chains strongly bind water and form viscous or gel networks, making them powerful texture modifiers and water-structuring agents in food systems (John et al., 2025; Yu et al., 2021; Sánchez et al., 2023). John *et al* .(2025) noted that these hydrocolloids are widely used to control water mobility, viscosity and gel strength in baked products, thereby competing with starch for available water during heating.

During heating in excess water, starch granules swell and undergo gelatinization as hydrogen bonds in both crystalline and amorphous regions are broken. This process causes amylose to leach into the surrounding medium and results in increased viscosity and water retention capacity (Yu et al., 2021). When cooled, retrogradation occurs as amylose, followed by amylopectin, reassembles into more ordered, crystalline structures. This reformation leads to gel firming, greater hardness, and water expulsion (syneresis), which contributes to staling in starch-based foods (Yu et al., 2021; Woodbury et al., 2022; K. et al., 2023).

Seaweed-derived hydrocolloids create three-dimensional gel networks either through helix formation and aggregation (as in agarose) or via sulfated galactan backbones. These structures can have their strength and elasticity adjusted based on their detailed structure and degree of sulfation (Montes et al., 2024; Beaumont et al., 2021; Sánchez et al., 2023). Non-starch hydrocolloids like carrageenan and other gums are known to interfere with amylose–amylose and amylopectin–amylopectin interactions, thereby reducing starch retrogradation in a concentration-dependent way, especially during prolonged storage (K. et al., 2023). By limiting chain mobility and structuring water within their networks, these galactan-based gels help delay recrystallization, decrease syneresis, and preserve a softer, more cohesive crumb in starch-rich baked goods over time (Montes et al., 2024; Yu et al., 2021; Woodbury et al., 2022; K. et al., 2023).

Pigment Transformation and Off-flavour volatile kinetics

The reduction in colorimetric score from 4.05 (P0) to 2.40 (P4) was likely due to the thermal sensitivity of red algal pigments, especially phycoerythrin, during processing conditions that reach or surpass typical denaturation temperatures for phycobiliproteins (Pereira et al., 2020; Sharma et al., 2021; Sun et al., 2023). Zepeda et al. (2024) and Hewa et al. (2024) noted that Gracilaria spp. have a complex pigment composition, including chlorophyll a, carotenoids like β-carotene and zeaxanthin, and abundant phycobiliproteins mainly composed of phycoerythrin, which give the characteristic red-purple color of the thallus.

During baking, when crumb temperatures reach around 95–98 °C and crust temperatures go beyond 180 °C, phycobiliproteins like phycoerythrin suffer significant thermal degradation and a decrease in color intensity (Pereira et al., 2020; Sharma et al., 2021; Sun et al., 2023). Phycoerythrin is a pigment–protein complex where open-chain tetrapyrrole chromophores (phycoerythrobilins) are covalently attached to the apoprotein. Heat causes unfolding and structural damage to this complex, speeding up pigment breakdown and color fading (Sun et al., 2023). The heat-sensitive nature of phycoerythrin, with degradation apparent even at moderate temperatures, is well known in both macroalgae and microalgal systems used as food colorants (Sharma et al., 2021; Sun et al., 2023). This denaturation and chromophore degradation align with the darker, unconventional crumb coloration seen at higher inclusion levels rich in red algal pigments (Pereira et al., 2020; Hewa et al., 2024; Sun et al., 2023).

The volatile profile of seaweed-based products is influenced by various volatile organic compounds (VOCs), including aldehydes and sulfur compounds, which strongly impact marine-like aromas (Coleman et al., 2022; Li et al., 2023; Trigueros et al., 2025; Cotas et al., 2020; Matos et al., 2024). Seaweeds and other algae produce key seafood-related volatiles like dimethyl sulfide and aldehydes derived from fatty acids, contributing to fishy or marine notes in food products (Coleman et al., 2022; Li et al., 2023; Trigueros et al., 2025). Lactic acid fermentation is known to acidify plant-based substrates and significantly alter volatile profiles by decreasing aldehydes and off-flavor compounds, while increasing esters and organic acids with sour or fruity aromas (Nicolotti et al., 2025; Sah et al., 2024; Zhang et al., 2022). In systems based on cereals, cassava, and legumes, lactic acid bacteria produce lactic and acetic acids along with esters such as ethyl acetate, which add sour and fruity notes and can help mask green, beany, or other undesirable off-flavors (Nicolotti et al., 2025; Sah et al., 2024; Zhang et al., 2022).

At low to moderate levels of adding algal biomass, fermentation-derived acids and esters often dominate the headspace, reducing the perception of marine VOCs and maintaining acceptable aroma scores (Nicolotti et al., 2025; Sah et al., 2024; Zhang et al., 2022). Nonetheless, dried seaweeds, especially Gracilaria, contain numerous VOCs such as aldehydes, alcohols, ketones, and other strong odorants that give their characteristic aroma (Li et al., 2023; Trigueros et al., 2025). As more seaweed powder is added, the total amount of algal VOCs increases and may overwhelm the masking effect of the sour–fruity volatile matrix, resulting in more noticeable marine or seafood-like notes (Coleman et al., 2022; Li et al., 2023; Trigueros et al., 2025; Matos et al., 2024). This change in aroma balance with higher seaweed substitution matches reports that sulfur- and lipid-derived algal volatiles contribute to “seafood” or “fishy” sensory impressions, which can be unpleasant in traditional baked goods for consumers unfamiliar with these flavors (Coleman et al., 2022; Li et al., 2023; Trigueros et al., 2025; Matos et al., 2024).

Market Dynamics and Global Scalling Potential

Positioning the P2 Gracilaria–Mocaf bread commercially connects three key factors: the rising demand for better gluten-free products, the use of local cassava-based flours, and the rapid growth of sustainable "blue food" value chains (Yusuf et al., 2025; Nilsson et al., 2022; Aguiar et al., 2021).

Commercial Opportunity in the Gluten-Free Segment

Demand for gluten-free bread is increasing due to celiac disease, gluten-related disorders, and lifestyle choices. However, commercial gluten-free breads are often criticized for their low protein, fiber, and mineral content, along with frequent reliance on refined starches like rice, corn, or tapioca (Capriles et al., 2023; Aguiar et al., 2021). Market reviews confirm that gluten-free breads generally have lower protein levels, variable and often low fiber, limited micronutrient fortification, and sometimes a high glycemic index (Aguiar et al., 2021).

P2 directly addresses this gap by enriching Mocaf bread with Gracilaria, which raises crude fibre content to 19–22% while maintaining acceptable sensory qualities (Yusuf et al., 2025). Incorporating seaweed into bakery products and biscuits reliably boosts dietary fibre and mineral levels, all while remaining sensorially acceptable at levels around 2–4% (Yusuf et al., 2025; Turuk & Banerjee, 2023; Cahya et al., 2025; Quitral et al., 2021). This makes P2 a functional, high-fibre, clean-label option in a market where nutritional quality is a significant unmet need (Capriles et al., 2023; Aguiar et al., 2021).

Local Cassava Systems and Economic Relevance

Mocaf, produced by lactic fermentation of cassava, is promoted as a cost-effective, locally available alternative to wheat that enhances food security and decreases reliance on imported wheat (Triwitono et al., 2024; Yusriana et al., 2025; Patriani & Rosadi, 2023; Apriliani & Mulyadi, 2022). Research indicates that Mocaf can effectively replace wheat in various bakery and snack foods, achieving good consumer acceptance and economic benefits (Triwitono et al., 2024; Yusriana et al., 2025; Patriani & Rosadi, 2023). Incorporating Gracilaria into Mocaf bread elevates a local cassava value chain into a higher-value, gluten-free functional product, thereby strengthening domestic food innovation and market diversification (Yusuf et al., 2025; Triwitono et al., 2024; Yusriana et al., 2025; Patriani & Rosadi, 2023; Apriliani & Mulyadi, 2022).

Blue Food and Sustainability Positioning

Seaweed plays a key role in the emerging blue economy, valued for its rapid growth, high carbohydrate and fibre levels, and its ability to be cultivated without requiring arable land, freshwater, or fertilizers (Ayala et al., 2024). Studies on seaweed-based biorefineries and SCOs indicate that macroalgae can produce competitive products with significant climate and land-use benefits compared to many terrestrial crops, as long as the processes are energy-efficient and supply chains are optimized (Nilsson et al., 2022; Amponsah et al., 2023; Ayala et al., 2024).

Life cycle assessments indicate that the environmental impact of seaweed systems is primarily driven by fuel consumption and artificial drying, making drying and energy sourcing critical points for achieving low-carbon growth (Nilsson et al., 2022; Amponsah et al., 2023; Ayala et al., 2024). Using solar or low-impact drying methods at coastal locations aligns with the recommended improvements for developing sustainable seaweed-based value chains (Nilsson et al., 2022; Amponsah et al., 2023; Ayala et al., 2024). This strategy enables P2 to be promoted not only as gluten-free and high in fiber but also as part of a low-carbon blue-food innovation pathway (Nilsson et al., 2022; Ayala et al., 2024).

Industrial Scaling and Ingredient Strategy

The industrial adoption of P2 hinges on the availability of standardized seaweed powders and efficient processing logistics. Research on seaweed bakery products and functional ingredients highlights that finely milled seaweed powders, moisture control, and consistent quality are crucial for ensuring reproducible dough behavior and sensory qualities (Turuk & Banerjee, 2023). Similarly, studies on Mocaf production emphasize that fermentation conditions and flour properties need strict regulation to meet industrial standards and enable broad use as a wheat alternative (Triwitono et al., 2024; Apriliani & Mulyadi, 2022).

Seaweed's natural water-binding and functional qualities allow it to substitute or lessen the need for synthetic hydrocolloids and other additives in formulated foods (Turuk & Banerjee, 2023; Cahya et al., 2025; Quitral et al., 2021). Evaluation of Gracilaria and similar species as functional ingredients reveals high fiber and mineral levels, along with bioactive properties that can enhance value in the functional food sector (Cahya et al., 2025). This facilitates a simpler, cleaner-label ingredient list and potential cost reductions by replacing imported wheat, refined starches, and industrial gums (Triwitono et al., 2024; Turuk & Banerjee, 2023; Cahya et al., 2025).

Broader Implications

The implications are that incorporating seaweed into staple foods could promote improvements in nutrition, sustainability, and local economy. Hossain et al. (2021) examined the role of seaweed farming in achieving sustainable development goals and demonstrated that seaweed farming could bolster coastal livelihoods and enhance food system resilience. This research aligns with that idea by linking seaweed production to a marketable bread product with practical local applications.

The findings suggest that future food systems may require more hybrid products blending terrestrial and marine ingredients. Colombo et al. (2022) examined circularity and sustainability in blue food systems and highlighted the potential of low-impact aquatic resources to contribute more significantly to food innovation. This study supported that perspective by showing that blue-food ingredients could be added to bakery products without compromising consumer appeal. This research, therefore, has significance beyond just the one product. It indicates that integrating local ingredients can evolve into a viable food-system strategy rather than merely an experimental idea. This is particularly important because it opens a pathway to applying circular-economy principles to everyday food products.

Conclusion

In conclusion, the study found that replacing 4% of flour with Gracilaria yielded the best Mocaf bread, as it offered the highest nutritional benefits along with appealing sensory qualities. Yusuf et al. (2025) explored similar blue-food bakery innovations and observed that optimal results were typically achieved at moderate inclusion levels rather than at the highest substitution points. The results indicated that seaweed-enriched Mocaf bread has potential as a gluten-free, locally sourced, and sustainable bakery option. Moreover, the study highlighted that successful food innovation requires balancing functionality, acceptability, and practicality for industry application.

Overall, the study strengthened the emerging evidence that seaweed-based products can transition from experimental ideas to regular food items. Gephart et al. (2021) examined the environmental impacts of blue foods and demonstrated that these ingredients could promote more sustainable diets. Building on this research, the current study illustrated how blue-food principles could be practically applied to create a bakery product that is both feasible and meaningful.

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