



Heavy Metal and Nutritional Profiles of *Sargassum crassifolium* Flour from Tomini Bay

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ABSTRACT

Sargassum crassifolium is a nutrient-dense brown macroalga with significant potential as a functional food ingredient, yet its utility is often constrained by its capacity to bioaccumulate contaminants in anthropogenically stressed coastal environments. This study evaluates the proximate composition, macro-mineral profiles, and heavy metal concentrations of *S. crassifolium* flour harvested from Kaisomaru, Tomini Bay, to determine its safety and nutritional viability for industrial applications. Nutritional composition was analyzed using AOAC-standardized methods, while spectrophotometric techniques were employed to quantify essential minerals (Ca, Mg, Na, K, Fe) and toxic heavy metals (Cd and As). Results indicate that the seaweed is rich in dietary fiber and ash with low lipid content, confirming its status as a promising source of essential minerals, particularly calcium. However, the heavy metal assessment reveals a critical safety breach regarding arsenic (As) concentrations, which consistently exceed maximum residue limits established by the Indonesian National Standard (SNI 2690:2015). This bioaccumulation is driven by the structural "egg-box" configuration of the alginate-rich cell wall matrix, which facilitates the non-selective binding of both essential and toxic ions. Consequently, the study concludes that direct use of this raw biomass is restricted due to food safety risks. These findings establish that standardized post-harvest detoxification benchmarks, such as selective leaching or ionic pre-treatment, are mandatory to mitigate toxic metal burdens while preserving the nutritional integrity of the biomass, providing a necessary baseline for future functional food development.

INTRODUCTION

The global demand for alternative, sustainable, and nutrient-dense food resources has accelerated significantly. Marine macroalgae, commonly known as seaweeds, have emerged as highly viable candidates to address food security challenges due to their rapid growth rates, lack of requirement for arable land, and exceptionally rich nutritional profiles (FAO, 2022). Among the various classes of macroalgae, brown seaweeds (Phaeophyceae), particularly the genus *Sargassum*, are well-regarded for their high concentrations of dietary fibers, essential amino acids, polyunsaturated fatty acids, and functional polysaccharides such as alginate and fucoidan (Matos et al., 2024). In Indonesia, *Sargassum crassifolium* represents an abundant yet underutilized marine resource with significant potential to be processed into functional food ingredients. Seaweed flour, in particular, could systematically enhance macro-mineral and micronutrient supply in human diets (Herliany et al., 2023). Beyond their dietary value, the biological structure of brown seaweeds presents a "dual-edged sword" in food applications. The cell walls of *S. crassifolium* are intrinsically rich in alginic acid and sulfated polysaccharides containing functional carboxyl, hydroxyl, and amino groups (Alsaei et al., 2026). These biochemical features exhibit an exceptionally high affinity for binding divalent and trivalent metallic ions, granting the macroalgae powerful bioabsorbent capabilities (Ordóñez et al., 2023). Consequently, while *Sargassum* species can efficiently accumulate beneficial minerals, such as calcium, potassium, and magnesium, from seawater, they simultaneously bioaccumulate toxic heavy metals from their surrounding environment, often acting as natural bioindicators of marine pollution (Astriani et al., 2024). This high bioaccumulation capacity creates a critical intersection between nutritional optimization and chemical food safety (Arifiyana et al., 2023).

The ecological integrity of the marine habitat plays a decisive role in determining the safety of seaweed-derived products. Tomini Bay, located in northeastern Indonesia, is one of the largest and most biologically diverse semi-enclosed bays globally. However, this vital ecosystem is increasingly subjected to severe anthropogenic pressures, including unregulated coastal development, agricultural runoff, and heavy metal discharges originating from artisanal and small-scale gold mining (ASGM) activities in adjacent watersheds. Persistent pollutants, specifically non-essential heavy metals such as cadmium (Cd) and arsenic (As), are discharged into the aquatic environment and eventually enter the marine food web. Because *S. crassifolium* efficiently sequesters these toxic metalloids from the water column, evaluating its toxicological profile is paramount prior to advocating for its widespread integration into the food chain.

Despite the widespread distribution of *Sargassum* species throughout the Indonesian archipelago, comprehensive studies simultaneously evaluating the proximate composition, mineral profile, and toxic heavy metal concentrations of *Sargassum crassifolium* from Tomini Bay remain remarkably scarce (Cokrowati et al., 2024). Most existing literature





focuses either on industrial wastewater bio-adsorption or isolated alginate extraction metrics (Ordóñez et al., 2023; Herliany et al., 2023). A significant knowledge gap remains regarding the quantitative assessment of toxic metalloid accumulation, particularly arsenic, in *S. crassifolium* harvested from Tomini Bay and its compliance with the maximum permissible limits established by the Indonesian National Standard (SNI 2690:2015). Addressing this gap is essential to determine whether the nutritional value of *S. crassifolium* outweighs its potential chemical risks.

Therefore, this study aims to comprehensively evaluate the proximate composition, macro-mineral profiles, and heavy metal concentrations (Cd and As) of *S. crassifolium* flour harvested from Tomini Bay. By assessing the empirical alignment of these values with national and international food safety guidelines, this paper provides critical insights into the bioaccumulative risks and nutritional viability of wild-harvested brown macroalgae, establishing a baseline for necessary detoxification benchmarks in functional food manufacturing.

LITERATURE REVIEW

Taxonomy and Nutritional Value of *Sargassum crassifolium*

Sargassum crassifolium is a brown macroalga belonging to the class Phaeophyceae, order Fucales, and family Sargassaceae, which comprises one of the largest and most taxonomically diverse groups of marine macroalgae (Guiry, 2024). Species within the genus *Sargassum* exhibit considerable morphological diversity and phenotypic plasticity, making accurate species identification dependent on the integration of morphological and molecular evidence. Characteristic features include a differentiated thallus with leaf-like blades (phylloids), spherical air vesicles that provide buoyancy, and reproductive receptacles adapted to intertidal and shallow coastal habitats (Stiger-Pouvreau et al., 2023; Álvarez-Canali et al., 2024).

In addition to its ecological importance, *S. crassifolium* has gained attention as a promising marine resource for food and nutraceutical applications due to its favorable nutritional composition. Brown seaweeds generally contain high concentrations of dietary fiber and mineral ash while maintaining low lipid levels, rendering them attractive ingredients for developing healthy food products. Their carbohydrate fraction is dominated by structural polysaccharides, specifically alginate, laminaran, and sulfated fucoidans, which contribute to both desirable hydrocolloid properties and diverse biological activities, including antioxidant, anti-inflammatory, immunomodulatory, and prebiotic effects (Peñalver et al., 2020; Matos et al., 2024).

The nutritional quality of *Sargassum* is further enhanced by its moderate protein content and balanced essential amino acid composition, supporting its application as a sustainable fortifying ingredient for plant-based diets. Previous studies have reported that *Sargassum* flour typically contains high ash content (20–44%), moisture levels below 10%, and protein concentrations ranging from 10–15%, although these values vary depending on species, geographical location, environmental conditions, and harvesting season (Astriani et al., 2024). Such compositional characteristics highlight the potential of *S. crassifolium* as a functional food ingredient capable of improving nutritional quality while providing bioactive compounds with significant health benefits.

Biochemical Characterization of Heavy Metal Bioaccumulation

The structural biochemistry of brown seaweed cell walls plays a pivotal role in its dual capacity for nutrient uptake and heavy metal bioaccumulation. Unlike terrestrial plants, the cell wall matrix of *S. crassifolium* is predominantly composed of a cross-linked polymer network of alginic acid, fucoidan, and cellulose (Matos et al., 2024). Alginic acid, a linear copolymer of β -D-mannuronic acid (M-blocks) and α -L-guluronic acid (G-blocks), contains a high density of active carboxyl ($-\text{COOH}$) and hydroxyl ($-\text{OH}$) functional groups (Alsaedi et al., 2026; Ordóñez et al., 2023). Under natural marine pH conditions, these functional groups become deprotonated, creating negatively charged coordination sites that exhibit a strong electrostatic affinity for multivalent cations present in seawater (Torres-Narváez & Flores, 2025).

This phenomenon, commonly operating via ion exchange, complexation, and surface microprecipitation, allows the macroalgae to efficiently accumulate both macro-minerals (such as calcium, magnesium, and potassium) and trace elements necessary for its physiological development (Noyanti et al., 2023). However, this metabolic and physical mechanism is non-selective. Consequently, non-essential, highly toxic chalcophile and metalloid elements, such as cadmium (Cd^{2+}) and arsenic (As^{3+} or As^{5+}), are sequestered from the water column with equal or greater thermodynamic affinity, leading to significant bioaccumulation within the algal thallus (Bhernama et al., 2021; Ordóñez et al., 2023).

Food Safety Risks and Regulatory Thresholds for Toxic Elements

While the presence of essential minerals enhances the dietary value of macroalgae flour, the concurrent bioaccumulation of toxic heavy metals presents severe public health risks (Arifiyana et al., 2023). Arsenic (As) is a notorious metalloid classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC). Chronic ingestion of inorganic arsenic via contaminated food matrices is strongly linked to dermatological lesions, cardiovascular diseases, neurotoxicity, and various forms of visceral cancers (World Health Organization [WHO], 2018). Similarly, cadmium (Cd) is a persistent nephrotoxicant with an exceptionally long biological half-life in humans, capable of inducing severe renal dysfunction, bone demineralization (itai-itai disease), and reproductive





abnormalities (Arifiyana et al., 2023; WHO, 2018).

To mitigate these dietary hazards, food safety authorities have established strict maximum residue limits (MRLs) for toxic metals in marine-derived foodstuffs. Globally, the Codex Alimentarius Commission provides baseline reference values for contaminant thresholds in food and feed. Locally, the Indonesian National Standard (Standar Nasional Indonesia [SNI]) and the National Agency of Drug and Food Control (Badan Pengawas Obat dan Makanan [BPOM]) strictly regulate heavy metal limits for dried seaweed and seaweed-derived flour products. According to SNI thresholds for food ingredients, arsenic levels are rigorously monitored to prevent chronic dietary toxicity. When wild-harvested macroalgae biomass from anthropogenic-stressed ecosystems like Tomini Bay exceeds these legal limits, raw utilization is strictly prohibited, necessitating targeted post-harvest mitigation or chemical detoxification processes before it can be safely integrated into the commercial food supply chain (Badan Pengawas Obat dan Makanan [BPOM], 2018; Badan Standardisasi Nasional [BSN], 2015, 2018).

METHOD

Sample Collection and Post-Harvest Processing

Wild-harvested samples of the brown macroalgae *Sargassum crassifolium* were collected from the coastal waters of Kaisomaru, Tomini Bay, Gorontalo, Indonesia. The precise coordinates of the sampling locations are detailed in Figure 1. The fresh biomass was thoroughly washed on-site with seawater to remove extraneous marine debris, epiphytes, and adherent sand, followed by a final rinse with distilled water to eliminate surface salinity. The seaweed was subsequently dried by air-drying for 40 hours, following a modified standardized protocol for brown macroalga post-harvest dehydration to preserve structural and nutritional integrity (Templonuevo et al., 2025), until the thalli reached a brittle state, characterized by their ability to snap easily, and exhibited a dominant brown color. The dried material was pulverized using an electric laboratory blender and sieved through a 60-mesh screen to obtain a homogenous *Sargassum crassifolium* flour. The resulting flour was sealed in airtight, light-protected polyethylene bags and stored in a desiccator at room temperature (25°C) until further chemical analysis.



Figure 1. Coordinates of the sampling location

Proximate Composition Analysis

The proximate composition of the *Sargassum crassifolium* flour, including moisture, ash, crude protein, crude fat, and carbohydrate content, was determined following the standardized procedures of the Association of Official Analytical Chemists (AOAC, 2005). Moisture content was quantified via oven-drying at 105°C until a constant weight was reached. Total ash content was measured using the dry-ashing method in a muffle furnace at 350°C until complete organic matter combustion was achieved. Protein content was determined using the micro-Kjeldahl technique, employing a nitrogen-to-protein conversion factor of 6.25. Crude fat was extracted via the Soxhlet method using n-hexane as the solvent at 70°C. Finally, the carbohydrate content was calculated 'by difference' by subtracting the sum of the moisture, ash, protein, and fat percentages from 100%.

Mineral Content Analysis

The mineral profile, comprising calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and iron (Fe), was determined through wet digestion, following the procedures established by Jannah et al. (2024). A 1.0 g sample was digested using a mixture of concentrated acids to ensure complete organic matrix destruction. The resulting solution was analyzed using UV-Vis spectrophotometry, with specific colorimetric reagents employed to form complexes for each mineral (e.g., 1,10-phenanthroline for Fe, calmagite for Mg, and tannic acid for Ca). Mineral concentrations were quantified against an external standard calibration curve and are reported as a percentage (w/w).





Heavy Metal Content Analysis

The concentrations of cadmium (Cd) and arsenic (As) were analyzed following standardized multi-element quantification protocols (BSN, 2021). A 1.0 g sample was digested using a mixture of nitric and hydrochloric acids until a clear solution was obtained. The analytes were determined via UV-Vis spectrophotometry utilizing specific complexing reagents designed for metal detection, such as dithizone for Cd and ammonium molybdate for As. Quantitative analysis was performed based on a standard calibration curve, with final results expressed in mg/kg.

Data Assessment and Statistical Analysis

All experimental measurements were performed in triplicate ($n = 3$), and analytical data are presented as mean values $\pm$ standard deviation (SD). To assess compliance with food safety regulations, heavy metal concentrations (Cd and As) were compared against the maximum residue limits (MRLs) established by the Indonesian National Standard (SNI 2690:2015). Statistical data were processed using Microsoft Excel to evaluate potential safety constraints.

RESULT

Proximate Composition

The macro-nutritional profile of *Sargassum crassifolium* flour harvested from Kaisomaru waters, Tomini Bay was evaluated through comprehensive proximate analysis. The results, compiled from triplicate measurements, are presented in Table 1.

Table 1. Proximate composition of *Sargassum crassifolium* flour

Nutritional Component	Content (% Dry Weight)
Ash	37.15 $\pm$ 1.60
Moisture	11.28 $\pm$ 0.16
Fat	4.40 $\pm$ 0.48
Protein	12.18 $\pm$ 0.38
Carbohydrate	37.20 $\pm$ 2.09

Note: Values are expressed as mean $\pm$ standard deviation ($n = 3$)

The proximate data indicate that ash and carbohydrates were the predominant constituents, accounting for 37.15% and 37.20% of the dry weight, respectively. The moisture content (11.28%) remained well below the critical 12% threshold, a finding that underscores the efficiency of the post-harvest dehydration process in ensuring long-term storage stability. Furthermore, the protein and lipid contents were recorded at 12.18% and 4.40%, respectively, reflecting the typical low-fat profile characteristic of marine macroalgae.

Mineral Profile

The elemental analysis focused on quantifying essential macro-minerals (Ca, Mg, Na, K, Fe) to determine the nutritional value of the seaweed flour. The quantitative distribution of these minerals is detailed in Table 2.

Table 2. Mineral composition of *Sargassum crassifolium* flour

Mineral	Concentration (% Dry Weight)
Calcium (Ca)	23.00 $\pm$ 0.00
Magnesium (Mg)	4.25 $\pm$ 0.00
Sodium (Na)	2.17 $\pm$ 0.00
Potassium (K)	0.33 $\pm$ 0.01
Iron (Fe)	0.93 $\pm$ 0.01

Note: Values are expressed as mean $\pm$ standard deviation ($n = 3$)

The elemental profiling demonstrates a profound capacity of *S. crassifolium* to sequester minerals from the marine environment. Calcium was identified as the most abundant mineral (23.00%), followed by magnesium, sodium, iron, and potassium. Notably, the calculated Na/K ratio was approximately 6.50, a value that provides critical insights into the ionic balance of the sample.

Heavy Metal Accumulation

To ensure food safety and regulatory compliance, the concentrations of toxic heavy metals, specifically cadmium (Cd) and arsenic (As), were determined and benchmarked against the standards established by the Indonesian National Standard (SNI 2690:2015) (BSN, 2015). The analytical findings are summarized in Table 3.





Table 3. Heavy metal concentrations of *S. crassifolium* flour compared to SNI 2690:2015

Heavy metal	Concentration (mg/kg Dry Weight)	SNI 2690:2015 Limit
Cadmium (Cd)	0.10 ± 0.00	0.1 mg/kg
Arsenic (As)	1.32 ± 0.08	1.0 mg/kg

Note: Values are expressed as mean as standard deviation ($n = 3$)

The toxicological assessment revealed a significant discrepancy between the two metals analyzed. Cadmium (Cd) concentration (0.10 mg/kg) was within the maximum permissible limit established by SNI 2690:2015. In stark contrast, the Arsenic (As) concentration (1.32 mg/kg) exceeded the regulatory threshold of 1.00 mg/kg. This critical breach indicates a bioaccumulation of toxic metalloids, suggesting that seaweed from this coastal ecosystem requires careful monitoring before commercial consumption.

DISCUSSION

Nutritional Assessment and Industrial Potential of the Proximate Profile

The proximate profile of *Sargassum crassifolium* flour demonstrates a composition suitable for functional food applications. The high ash content (37.15%) is characteristic of brown macroalgae, reflecting their remarkable capacity to sequester inorganic minerals from the marine environment (Astriani et al., 2024). Regarding stability, the moisture content (11.28%) remains below the 12% critical threshold, effectively minimizing microbial spoilage. Although the protein content (12.18%) is modest compared to conventional protein sources, it remains comparable to other *Sargassum* species, indicating its potential as a nutritional supplement. Furthermore, the low lipid content (4.40%) enhances shelf-life stability by reducing susceptibility to oxidative rancidity. Finally, the carbohydrate fraction, predominantly composed of structural polysaccharides like alginate and fucoidan, confers significant technological functionality, supporting its potential as a natural stabilizer or thickener in food formulations (Matos et al., 2024; Diestra-Balta et al., 2026).

Mechanisms of Mineral Enrichment and the Dual Nature of Alginate

The high mineral concentration, specifically Calcium (23.00%), Magnesium (4.25%), and Sodium (2.17%), highlights the significant nutritional value of *S. crassifolium*. The biochemical driver behind this mineral density is the unique structural arrangement of the brown seaweed cell wall. The matrix is rich in alginic acid, which forms a spatial conformation known as the "egg-box" model, characterized by a high thermodynamic affinity for binding divalent cations such as Ca^{2+} and Mg^{2+} via ion-exchange mechanisms (Alsaedi et al., 2026). The calcium concentration observed in this study was higher than that reported for *S. crassifolium* from Bali (Herliany et al., 2023), suggesting that the Kaisomaru coastal environment may facilitate more efficient mineral uptake. However, the Na/K ratio of approximately 6.50, which exceeds the World Health Organization (2012) recommendation of <1.0 , indicates that processing strategies to reduce sodium levels are necessary if intended for direct human consumption. Furthermore, the presence of iron (0.93%) underscores the potential of *S. crassifolium* as a nutritional supplement, as iron is a vital micronutrient for hemoglobin synthesis and oxygen transport.

Toxicological Safeguards: The Arsenic Enigma and Food Safety Risks

The toxicological assessment reveals a critical safety profile for *S. crassifolium* flour. While cadmium (Cd) concentration (0.10 mg/kg) remains within the permissible baseline established by the Indonesian National Standard (SNI 2690:2015) (BSN, 2015), the arsenic (As) concentration (1.32 mg/kg) significantly exceeds the regulatory threshold of 1.00 mg/kg. This excessive accumulation is primarily attributed to the chemical mimicry between arsenate (AsO_4^{3-}) and phosphate (PO_4^{3-}); owing to their structural similarity, arsenate is inadvertently taken up by *Sargassum* through high-affinity phosphate transport systems (Cipolloni et al., 2024).

Furthermore, the environmental context of Kaisomaru waters complicates this accumulation profile. The complex geochemical and anthropogenic composition of coastal waters often induces competition for functional binding sites within the algal biomass, which inherently complicates the selective removal of toxic metalloids during post-harvest processing (Ordóñez et al., 2026). This breach of safety standards suggests that the coastal ecosystem may be subject to localized anthropogenic pressures, potentially including runoff or industrial discharge. Given that chronic arsenic exposure is correlated with severe systemic health risks, including carcinogenicity and organ toxicity (WHO, 2018), the utilization of untreated *S. crassifolium* flour as a direct food ingredient is strictly constrained by current safety regulations. To leverage the immense nutritional value of this biomass, it is mandatory to develop and implement standardized pre-treatment mitigation protocols, such as controlled mild acid washing or specialized water leaching, to selectively mobilize and strip toxic metalloids from the alginate matrix. Ultimately, continuous environmental monitoring and rigorous toxicological verification are essential to ensure the sustainable and safe utilization of this marine resource for the food industry.





CONCLUSION

This study confirms that *Sargassum crassifolium* from Tomini Bay is a nutrient-dense biomass with significant potential as a functional food ingredient, characterized by high dietary fiber and mineral content. However, the evaluation of heavy metal concentrations reveals a critical safety breach regarding arsenic (1.32 mg/kg), which exceeds regulatory thresholds due to phosphate-arsenate chemical mimicry. While cadmium levels remain within the safety limits set by SNI 2690:2015, the arsenic accumulation poses a significant risk that restricts the direct use of this raw biomass. Consequently, this study establishes that standardized detoxification benchmarks, such as selective leaching or ionic pre-treatment, are mandatory to ensure safety while preserving the nutritional integrity of the biomass for industrial applications. These findings provide a necessary baseline for developing processing strategies to mitigate contamination in mineral-rich marine resources.

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