Review Article

Mapping Global Research on Seaweed-Based Beverages: A Bibliometric Analysis of Bioactive Compounds, Sensory Attributes, and Safety Considerations

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Abstract
The bioactivity of seaweeds is garnering increasing attention, highlighting the potential of seaweed-infused beverages as sustainable functional foods. However, research in this area remains limited and often lacks an integrated consideration of functional efficacy, sensory acceptance, and safety. In this review, we conducted a bibliometric analysis of global research trends in seaweed-based beverages using Scopus-indexed literature published between 2005 and 2025. Performance analysis was conducted using the Biblioshiny interface, while co-authorship mapping and keyword co-occurrence analyses were performed using VOSviewer. A total of 222 documents were identified, with an increasing trend in publication output, predominantly from Asian and European countries. Keyword analysis revealed that bioactivity-related research was strongly dominated by antioxidant activity, fucoidan, and carotenoids. In contrast, sensory-related research remained marginal, with flavor being the only explicitly identified sensory keyword. Notably, safety emerged as a prominent research theme, with strong links to formulation and processing, particularly regarding iodine. These findings highlight important translational gaps and emphasize the need for integrated research frameworks that simultaneously consider functional efficacy, sensory quality, and safety to facilitate the development and commercialization of seaweed-based functional beverages.

Keywords: Bibliometric analysis, Bioactive compounds, Functional food, Safety assessments, Sensory evaluation

1 Introduction

Sustainable Development Goals (SDGs) 3 targets on good health, well-being, prevention of sickness and promotion of healthy lifestyles. Micronutrient deficiency, protein-energy malnutrition and diet-related non-communicable diseases (NCDs), particularly obesity and type 2 diabetes, continue to be a challenge of public health at the global level [1]. On the other hand, sugar-sweetened beverage (SSB) consumption is high worldwide and is associated with overweight/obesity and poor dietary quality. The World Health Organization (WHO) advises that free sugar intake should be less than 10% of total energy intake, with additional health benefits expected to occur at the lower limit of 5% [2]. High levels of SSB consumption are linked with obesity and other diet-related non-communicable diseases (NCDs), making it essential to consider alternatives [3].

Multiple studies have associated the intake of added sugar-containing soft drinks with an increase in caloric intake and metabolic deregulation, including obesity, type 2 diabetes mellitus, cardiovascular diseases, or other chronic conditions [4]-[6]. Consequently, the food industry is under increasing pressure to create functional and low-calorie or no-calorie beverage concepts. As a result, functional and plant-based drinks are becoming increasingly popular as alternatives to soft drinks. Therefore, marine algae (macroalgae and microalgae) have been highlighted as attractive raw materials with great nutrient density and a broad range of bioactive components like sulphated polysaccharides, polyphenols, carotenoids, sterols, vitamins, minerals or long-chain omega-3 fatty acids [7]. With the knowledge of their antioxidant, anti-inflammatory, antidiabetic and lipid-modulating properties [8], algae-derived ingredients appear to be useful for functional food and beverage applications. As these beverages provide bioactive compounds that might confer antioxidant, metabolic and anti-inflammatory functions, they may play a role in health promotion and prevention of diet-related non-communicable diseases (NCDs), which confers an additional, more specific pathway for supporting untargeted SDG 3 beyond their general nutritional value.

Marine macroalgae, better known as seaweeds, are multicellular, photosynthetic eukaryotes which can further be classified into red (Rhodophyta), brown (Phaeophyceae) and green algae (Chlorophytes), according to pigment composition and structural functions [9]. The techno-functional traits and the food application relevance can be established by some characteristic composition and functional peculiarities in each group. Although the functional ingredient properties of macroalgae and microalgae, this paper focuses on beverages derived from marine-origin seaweeds produced from macroalgal species that have been identified as dominating space in beverage-centric research and commercial product development with more directed methodologies.

Seaweeds are known to have potential applications for various uses (food ingredients, stabilisers and sources of functional compounds), but their use in beverages is somewhat limited by technical hurdles involving solubility, physicochemical stability and sensory acceptance, as well as safety guarantees. These materials have been sourced from both seaweeds and intertidal ecology, thus having the potential to contribute marine flavours or modify colour and/or textural properties; all of which can detract from consumer acceptance if they are not carefully optimised [10]. In addition, safety evaluation, such as iodine content and heavy steel bioaccumulation (for example Metals (e.g., arsenic, cadmium and lead), must be closely evaluated for compliance with food safety regulations to protect the consumer [11].

As such, seaweed beverages are an innovative food system that presents a new way to deliver exemplary marine-derived bioactive compounds through a consumer-friendly format, in response to the request for plant-based and sustainable health-protecting ventures. Although scientific interest is increasing, this research field is still fragmented among the fields of food chemistry, nutrition, sensorial sciences and food safety (with a strong proportion of the publications being product-specific or methodologically heterogeneous).

Bibliometric analysis is a quantitative tool that provides the methodology to analyze publishing patterns, thematic structure of domains, collaboration network and evolution pathways of research [12]; thus, enabling more objective and data-driven insights compared to narrative reviews. In this regard, a bibliometric analysis of published Scopus-indexed articles was conducted to map global research on seaweed-based beverages using Biblioshiny for R and visualization tools focusing on three interrelated thematic pillars: bioactive properties, sensory evaluation and safety assessment. This offers a strategic reference for researchers, product developers and policymakers, indicating publication trends, major themes of research, collaboration patterns between institutions/countries and future niche opportunities; this is the first comprehensive bibliometric analysis specifically focused on seaweed beverages to our knowledge.

2. Methodology

2.1 *Data source and search strategy*

For this bibliometric analysis, the Scopus database was used as our target data source because it effectively covers food science, marine biotechnology and functional food studies and its metadata is recorded in standardized formats with rich citation profiles for mapping exploration and performance evaluations [13], [14]. In that context, for this bibliometric analysis of functional food and marine bioresource research, we used the Scopus database as it is the most widely used database in this kind of study [15], which helps us to overcome bias because of its wide coverage in peer-reviewed literature.

To obtain a general overview of the historical evolution and current trends regarding research publications on seaweed-based beverages, papers indexed from 2005 to the last updated year of 2025 were retrieved and analysed (according to established bibliometric methods), allowing us to characterise publication patterns over time, research maturation, as well as emerging themes of this topic area [12]. The final search was on 15 December 2025 using the structured Boolean query (("seaweed-based beverage" or "seaweed beverage" or "seaweed drink") or ("seaweed" OR "macroalga" OR "marine algae" OR "red algae" OR,"brown algae") and ("beverage", "drink", "juice", "fermented beverage" or "functional beverage*)) in TITLE–ABS–KEY fields (Figure 1). The links and quantitative data generated were derived from the search results, but only for research articles or reviews published in open-access (English-language) journals to avoid repeating abstract content scores since English is already the global scientific standard. Analysis of bibliometric data (authorship, affiliations, abstracts, keywords, source title and cited references) was also exported as a CSV file for further analysis [16].

2.2 *Data preparation, cleaning and harmonization*

This study defined its data scope and ensured analytical rigor by employing a PRISMA-type screening workflow, following best practices for the transparent reporting of literature selection in review studies [17]. The first selection was made according to the title and abstract, and a verification search for author keywords and subjects. OpenRefine (v3.8.7.exe) was used to clean and standardize the data: a tool used for pre-processing bibliometric data [18].

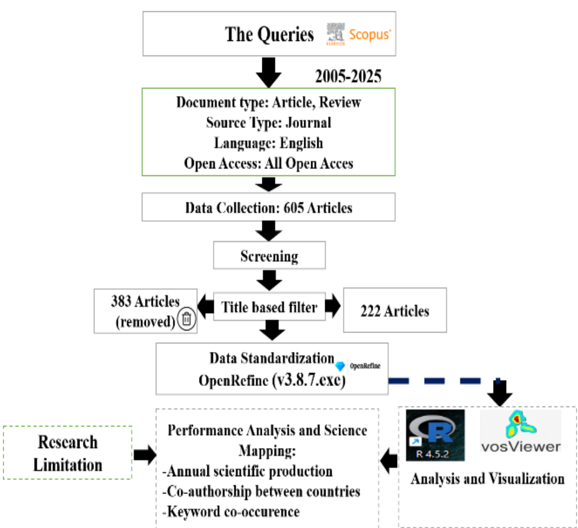

Figure 1: Literature search and bibliometric analysis workflow.

2.3 *Performance analysis*

The descriptive and evaluative bibliometric indicators were generated using Biblioshiny: the web-based graphical interface of the bibliometrix R-package [12]. Analyses focused on annual increases in publication output, as per standard bibliometric methodologies [19]. These indices provided a quantitative overview of the evolution, productivity and academic influence of seaweed-based beverage research over the specified period.

2.4 *Science mapping and network visualization*

Network analyses were conducted using VOSviewer (v1. 6. 20) [20]. The mapping strategies used were: (i) Use of co-authorship analysis to uncover collaboration networks between countries; (ii) Keyword co-occurrence analysis based on author keywords for revealing central themes and conceptual clusters. We normalized association strength to avoid frequency bias and then iteratively adjusted minimum occurrence thresholds until clusters were semantically interpretable (following VOSviewer methodological recommendations [20], [21]). Prior to mapping, they were enhanced through keyword cleansing (thesaurus-based unification and manual cleaning), reducing semantic redundancy and noise. Following up with supplementary Figure 2, we worked on OriginPro (OriginLab Corp., USA) [22] to facilitate a better visualization of trends in the scientific production.

3 Results and Discussion

3.1 *Scope of the search for seaweed-based beverages studies*

The bibliometric analysis provides a thorough summary of the temporal development, structural structure and research paths of studies involving the topic under investigation. Recent bibliometric analytics have shown that the strongest measures of overall research activity (number of publications per year) are also some of the best and most rapidly measurable indicators of thematic maturation, responsiveness to emerging challenges, and innovativeness [15], [23]. Temporal publication patterns have been frequently employed to ground knowledge of food and nutrition research in temporality (i.e., temporal disparities in thematic emphasis), thus paving the way for further investigation of geographical scope, collaborative networks and thematic evolution [16]. Annual scientific output is thus one of the key variables to be considered when interpreting trends in seaweed-based drinks sciences, as shown in Figure 2. This increase in research may also be driven by factors such as increasing international collaboration and global cooperation on research programs.

Specifically, one such annual publication differs over the years (2005–2015 period), as publication trends show (The trend has increased —except 2010 and 2018; all in all —not too much differently regarding year that might reach about 2020). Figure 2, in turn, indicates the increasing scientific interest and intensity of research being targeted towards this space. Annual scientific production appears to follow an ascending pattern over the studied period, with low research activity for the earliest years but a large growth from the 2010s to present (mid). The increase may signify a growing academic interest in the field fueled by factors like increasing consumer demand for functional foods, advances in food processing technologies, and more reliable interactions attributing positive health effects to bioactive components.

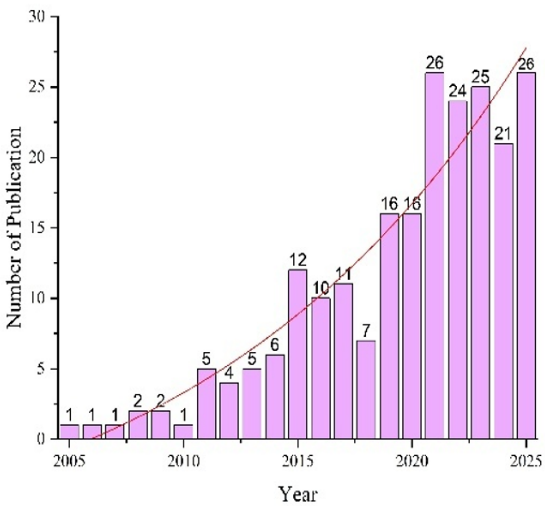

Figure 2: Annual scientific production related to seaweed-based beverages from 2005 to 2025.

The small yearly fluctuations for some of those years likely reflect shifts in funding interest or other methodological challenges. The annual growth of publications indicates a transition from a nascent to an established field of future functional food research. Analysis suggests patterns emerge across thematic evolution, collaboration behavior and research themes, respectively.

The almost linear increase in annual production of science on red seaweed beverages since circa 2015, on the other hand, indicates that this particular niche subset branch (sub-field) has become a well-developed area/function foods site of research. The functionality of this fruit as a functional food corresponds to the increasing consumer demand for natural bioactive compounds that propels plant-based beverages and sustainable food innovation at large [24].

A Scopus database was used to extract the countries' collaboration based on co-authored publications. Node size is representative of the number of publications and the link thickness indicates how strong the collaboration between authors is; all nodes mentioned are coloured according to the average year of publication (blue–older; purple –recent research activity). The global map shows applications of seaweeds in beverages (Figure 3), exhibiting several hubs and significant international connectivity. The node size indicates the number of collaborations that US, Japan and South Korea are clearly strong contributors, even clearer since they have larger node sizes (larger weight) compared to others, with many good links to these countries. Most of the previous studies were in Japan and US, while more recent publications reported higher uptake from South Korea, Australia, Ireland and some developing nations. The stepwise and functional-wise network structure is growing from regional to the global research landscape, according to international interest in developing and assessing the impact on seaweed-based beverages.

International co-author network analyses also show that these have become increasingly collaborative amongst fields, which reflects changes in the dynamics within these. Research activity has previously been concentrated in a few countries, but more recent publications indicate an increasing global interest. This expansion illustrates international recognition and future prospects for seaweed-based beverages as an important research area against the background of sustainable food systems, metabolic health and functional product development. Thus, global seaweed research becomes even more interdisciplinary [25].

Inside the keyword co-occurrence network (Figure 4), seaweed also consists central thematic research theme that links one cluster of themes to another. The first cluster is related to bioactivity and functional activity, characterized by the terms fucoxanthin, antioxidant activity, phenolic compounds and bioactivity. Processing and product development (fermentation, probiotics, beverage) is the other group. There were a few keywords showing relevance to functional low manufacturing ingredients (fucoidan and iodine) or stability (antimicrobial and stability). Across the network, terms related to quality and shelf-life considerations appear (e.g., carrageenan, shelf-life sustainability), whilst sensory-related characteristics, including flavor, are present simply as peripheral nodes in this network with weaker connections comparatively.

The structured framework of themes guided by keywords co-occurrence mapping unveils that seaweed-based beverages were mainly discussed in terms of basic quality parameters, bioactive compounds and fermentation process. As such, this is a very compound-centred functional territory where keywords like antioxidant activity, phenolic compounds and fucoxanthin rule the roost. All this contrasts with the observations made in building networks based on dimensions of relevance to the application (sensory properties, safety aspects), which displayed poor connectivity overall and therefore limited thematic integration across beverage development.

The keyword co-occurrence network (Figure 4) generated by VOSviewer again demonstrates the thematic imbalance uncovered during the bibliometric analysis: bioactivity-related terms (e.g., antioxidant activity; fucoxanthin; fucoidan) are structured centrally throughout the network, while application-oriented topics including flavor and

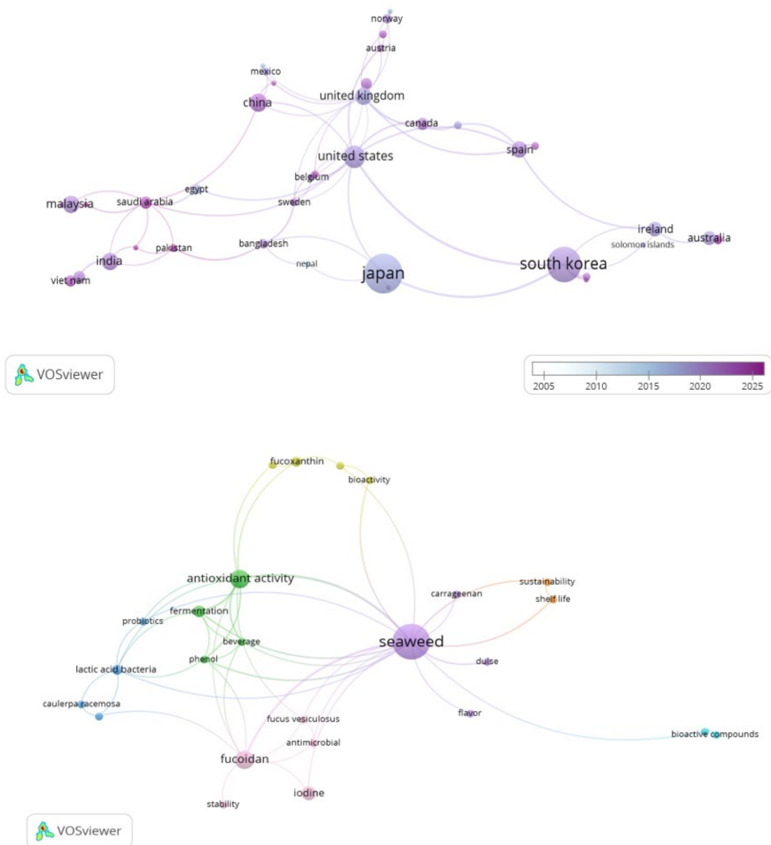

Figure 4: Keyword co-occurrence network based on author keywords in seaweed-based beverage research retrieved from the Scopus database. Node size represents keyword frequency, link thickness indicates co-occurrence strength, and colours denote thematic clusters.

shelf-life keywords as well as safety-related keywords occupy more peripheral positions and appear loosely connected to other regions of the network.

3.2 *Bioactive properties in seaweed-based beverage research*

The growing interest in the market regarding seaweed beverages is closely related to the exceptional variability of bioactive compounds of natural marine macroalgae. Seaweeds harbor a distinct mixture of polysaccharides, polyphenols, carotenoids, as well as proteins and other micronutrients, uniquely contributing to nutritional and health benefits compared with traditional terrestrial plant-based sources. They play a role in various biological activities, including antioxidant, anti-inflammatory, immunomodulatory and prebiotic effects, as well as antihypertensive and metabolic regulation [26]. Thereby, seaweed-derived ingredients have been extensively investigated as functional ingredients of the next-generation healthy beverages.

Basic physiological understanding of nutritional modulation, specifically via the positive health impact of marine-organisms-derived bioactives (e.g., from algae and seaweed) on complex beverage systems, is a trend with significance that extends beyond strictly nutraceutical concerns. Determining whether the active ingredient is suitable for beverage formulation requires evaluation of four critical factors: solubility in water, stability during processing and storage, bio accessibility, and sensory impact (taste and aroma), as well as interactions with other components of the beverage [27], [24]. Certain sulfated polysaccharides such as fucoidan, laminarin and other polysaccharides are good water-soluble compounds, while others example fucoxanthin and omega-3 fatty acids are lipophilic in nature which leads to poor solubility into aqueous systems therefore these must require encapsulation/emulsification approaches to enhance their delivery. Other than these health aspects, those derived from algae also provide some important functional properties that are thickening, texture modification and stabilizing [28]-[30]. Table 1 summarizes important bioactive compounds from seaweeds and their chemical classes, an overview of main biological activities and potential applications in beverages.

Functional ingredients related to health and technology: Support bioactive compounds like laminarin and alginate have gained the most attention due to their dual functionality in promoting healthiness and improving food quality. Apart from the purported metabolic regulation and gut health benefits, these polysaccharides provide important functionalities in liquid food systems by altering texture, viscosity and mouthfeel [63]. This new orientation of their multifunctional properties has transferred them from being health-promoting components to important constituents in developing novel and customer-cantered food formulations. In addition, the development of compounds such as ulvan, NAOS and bioactive peptide derivatives from seaweed opens an expansion of functional research targets beyond antioxidant activity to prebiotic effects, protein functionality and gut health modulation [64].

Lastly, the functional potential of seaweed-derived beverages needs to be further considered with regard to synergetic and antagonistic interactions among bioactive compounds. Compared with isolated compounds, beverage matrices have many polysaccharides, phenolic compounds, carotenoids, proteins and minerals as well as other constituents that may interact with each other during processing and storage. This can create synergistic (through stacking complementary biological properties) or antagonistic effects (in terms of altering the stability, solubility, bioavailability or sensory properties of the compound) [26], [65].

Interactions between phenolic compounds and polysaccharides, for instance, tend to alter their physicochemical and functional characteristics, with recent evidence revealing even synergistic or antagonistic effects on antioxidant activity specific to brown seaweed [66]. A case in point is the supplementation of lipophilic carotenoids such as fucoxanthin, which requires emulsification or encapsulation to improve their stability and bioaccessibility when incorporated into aqueous beverages. In particular, oil-in-water emulsion systems can significantly enhance the bioaccessibility of fucoxanthin, depending on the type of emulsifier used [67]. These interactions can be altered by factors like pH, temperature, oxygen and light conditions that also affect the stability of bioactive compounds [68]. Thus, future studies should assess bioactive compounds in realistic beverage matrices instead of isolated-compound assays, with particular attention to combined functionality, stability and bioaccessibility.

Seaweed-based beverages are an important source of nutrients including micronutrients (vitamins and minerals), omega-3 fatty acids, sterols, chlorophylls and non-phlorotannin polyphenols. While these compounds are known to have some health benefits, they have mostly been studied for their compositional and nutritional properties rather than their functional contributions as bioactive ingredients.

3.3 *Sensory evaluation and consumer science perspectives in seaweed-based beverage research*

Sensory evaluation is an important but poorly studied component of seaweed beverage research. Although extensive research has been focused on the nutrition, bioactive compounds and functionality of these kinds of beverages, sensory properties like taste perception, aroma, mouthfeel or texture, overall acceptability and consumer preference have not received as much attention. As in most studies, sensory analysis is often conducted primarily at post-formulation stages but can be done more holistically as part of product design and optimization approaches.

This imbalance is a key challenge from a consumer science perspective. The presence of health-promoting compounds does not guarantee success in the marketplace, as consumer acceptance also stems from sensory impression and tasting experience [69]. Therefore, sensory issues should be assessed along with functional and nutritional targets at the early formulation stages of seaweed-based beverages. Ingredient formulations derived from seaweed have unique sensory characteristics that are likely to influence consumer perceptions and acceptance. These sensory characteristics include marine or oceanic aromas, which may be perceived as fresh and appealing by niche consumer groups but are often considered undesirable in mainstream beverage markets. Bitterness and astringency are also common sensory attributes of seaweed-based beverages and are primarily associated with phenolic compounds and sulfated polysaccharides. In addition, umami and savory notes may be advantageous in certain beverage categories but can conflict with consumer expectations for sweet-tasting beverages. The co-occurrences in the sensory-related keywords with phenolics and fermentation/bioactivity demonstrate a key trade-off to bottling seaweed-based beverages: compounds that provide health benefits can often lessen the palatability of products. A well-established concept in consumer science is the cost–benefit trade-off, whereby perceived healthiness and expected taste or liking may be negatively associated, reflecting the commonly observed “healthy = less tasty” heuristic [70].

Most published studies focus on bioactive compounds, antioxidant activity, fermentation process and functional implications for health promotion; sensory characterization is frequently a second objective. Consequently, the types of sensory tests most often performed by researchers are simple hedonic or acceptability tests using untrained or semi-trained consumers and mostly targeting exploratory product acceptance.

Some sophisticated sensory approaches such as Descriptive Sensory Analysis (DSA), Temporal Dominance of Sensations (TDS), and Temporal Check-All-That-Apply (TCATA) have yet to be widely applied to seaweed-based beverages, along with preference mapping. As a result, how and why sensory perceptions change during ingestion, or even what makes consumers like or dislike something, remains poorly understood today. Since significant sensory attributes related to seaweed-based ingredients, such as bitterness, marine notes, umami characters and lingering aftertastes, are often perceived only post-swallow [71] rather than at the actual first point of consumption, this is a key area for investigation.

In addition, comparatively fewer works have studied the drivers of acceptance related to consumers. Consumer preferences are not only based on sensory properties but also on expectations, the appearance of ingredients, similarity to backgrounds and health claims. Preliminary evidence on product labelling effects has been provided by previous research [72], [73]. Seaweed-based beverages also have an interesting role in the context of culture. Marine flavors are quite at home in places like East Asia, where seaweed consumption simply becomes a part of the everyday meal fabric. In contrast, potentially neophobic Western consumers may find these new flavors to be unfamiliar when they are included in beverage products expected to have fruity or sweet sensory profiles. The data from cross-cultural sensory studies are rare, and the limited generalisation of existing findings might thus contribute to explain why products derived from seaweeds and other algal ingredients have had low commercial success outside specific or niche markets.

One possible way to improve the functional and sensory quality of seaweed products is through fermentation. Through microbial metabolism, lactic acid bacteria plus any other microbial cultures can reduce undesirable marine and bitter notes, form organic acids and volatile aroma compounds that contribute to freshness, and create improved naturalness/authenticity perceptions. These changes can enhance the overall sensory quality and consumer acceptance [74], [75]. However, much of the work on fermentation has been across microbiological, biochemical and functional endpoints, with only a very limited number of studies systematically investigating the relationships between parameters of fermentation and hedonic consumer responses [74], [76]. Based on this, the fermentation technology of matching with sensory optimization and consumer preference analysis is limited, and further research is needed.

Future research should link progressive sensory methodologies with bioactive functionality, food processing technologies and consumer behaviour in order for the interactions of sensory perception, product formulation and health-related characteristics to be explained as influential factors on acceptance. An integrative framework can provide guidelines to develop and commercialize seaweed beverages as next-generation functional foods [77]. Building on these results from a multisensory perception perspective (Table 2) connects together the main sensory cues, their functional significance and the methods employed to assess consumer perceptions and product characteristics.

3.4 *Safety assessment in seaweed-based beverages research*

Despite growing interest in seaweed beverages, their safety remains less explored than their nutritional and functional properties. Limited studies have addressed contaminant exposure and compliance with food safety regulations, highlighting an important gap in developing safe and sustainable seaweed-based beverages. Iodine intake is the most researched of all safety issues regarding seaweed consumption. This elucidates one of the major motivations for investigation into iodine bioaccumulation capacity to date, and extends market opportunities to other algal species (*Laminaria*, *Saccharina* and *Undaria*) [88], [89]. Iodine contributes to the normal function of the thyroid, but excessive consumption can be linked to both thyroid dysfunction and health hazards. Although there are previous studies that have been directed on the determination of iodine in seaweed raw materials, fewer studies related directly to the iodine loading from beverage consumption have been performed.

Important variables such as serving size, intake frequency, bioavailability, and processing effects on iodine retention remain underreported. Therefore, future studies should incorporate realistic intake scenarios and consider the effects of processing, formulation, and storage on iodine content and consumer exposure. Particularly troubling from a regulatory standpoint. The European Food Safety Authority (EFSA) suggested a tolerable upper intake level (UL) of 600 µg/day for adults because frequent high iodine intakes can increase the risk of thyroid disorders [90]. But few studies of drinks have directly evaluated whether formulations are below recognized thresholds for safety. Hence, the compositional measurements can readily become dissociated from meaningful implications regarding consumer safety or regulatory compliance.

Other risks related to contaminants, besides iodine, are another practically counterfactual risk that needs further research. Seaweeds also have the capacity to bioaccumulate a variety of potentially toxic compounds (i.e., heavy metals) from the marine environment as well as other unknown inorganic pollutants [91]. Nevertheless, although the risk is well established, studies evaluating overall contaminant levels for seaweed beverages are relatively scarce. Because this data is so scarce, our knowledge of long-term safety risks associated with regular consumption of these products is also limited.

Table 1: Key seaweed-derived bioactive compounds, their chemical classes and functional roles in beverage systems (Part 1).

Bioactive compound	Chemical class	Main seaweed source	Reported content	Reported functional relevance	Practical formulation challenges	Refs
Fucoidan	Sulfated polysaccharide	Brown seaweeds (*Fucus, Undaria, Laminaria*)	1–33% DW; up to 55% in some *Laminaria* spp.	Antioxidant, anti-inflammatory, immunomodulatory	Water-soluble, but content and structure vary strongly with species, season, and extraction; molecular-weight control may be needed	[31]-[33]
Fucoxanthin	Carotenoid (xanthophyll)	Brown seaweeds (*Undaria, Sargassum, Fucus*)	0.013–5.41 mg/g DW	Antioxidant, metabolic regulation, anti-obesity potential	Poor water solubility (~0.5 ppm), light/heat/pH sensitivity; emulsification or encapsulation may be required	[34]-[36]
Carrageenan (κ-, ι-)	Sulfated galactans	Red seaweeds (*Kappaphycus, Eucheuma*)	8.6–26.4% DW in *K. alvarezii* from Indonesian farms	Texturizing, stabilizing; potential gut-related functionality	Excessive concentration can increase viscosity and alter mouthfeel; gelation depends on type, ions, and processing	[37]-[39]
Phenols/phlorotannins	Phenolic compounds	Brown seaweeds (*Ecklonia, Fucus*)	0.032–14% DW (GAE), depending on genus/extraction	Antioxidant, antimicrobial, enzyme inhibition	Extraction-dependent variability; high levels may contribute to bitterness/astringency and color	[40]-[41]
Laminarin	β-glucan polysaccharide	Brown seaweeds (*Laminaria, Saccharina*)	0–35% DW; commonly reported up to 33–35%	Immune modulation, antioxidant and metabolic effects	Content varies strongly with season; solubility and molecular structure influence beverage stability	[40], [42]
Alginate	Anionic polysaccharide	Brown seaweeds (*Laminaria, Macrocystis*)	~18–40% DW, depending on species	Thickening, stabilizing; potential satiety/glycemic effects	Strongly increases viscosity; excessive levels can negatively affect mouthfeel and beverage flow properties	[43], [44]
Agar / NAOS	Galactan-derived polysaccharide/oligosaccharides	Red seaweeds (*Gracilaria, Gelidium*)	Agar: ~10–30% DW commonly reported; NAOS is generated by hydrolysis rather than naturally accumulated	Prebiotic, antioxidant potential	Agar requires controlled dissolution/gelation; NAOS requires controlled enzymatic/acid hydrolysis and DP control	[45]
Ulvan	Sulfated heteropolysaccharide	Green seaweeds (*Ulva, Enteromorpha*)	~9–36% DW	Antioxidant, immunomodulatory, prebiotic potential	Extraction yield and molecular structure vary with pH, temperature and pretreatment; can affect viscosity and stability	[46], [47]
Bioactive peptides	Protein-derived peptides	Various macroalgae	No fixed native concentration; peptides are commonly generated by enzymatic/proteolytic hydrolysis	Antihypertensive, antioxidant	Hydrolysis degree, peptide size and bitterness need to be controlled; stability in beverage matrices requires evaluation	[48]

Table 1: Key seaweed-derived bioactive compounds, their chemical classes and functional roles in beverage systems (Part 2).

Bioactive compound	Chemical class	Main seaweed source	Reported content	Reported functional relevance	Practical formulation challenges	Refs
Other carotenoids	Carotenoids	Brown and green seaweeds	Total carotenoids commonly ~0.6–16.3 mg/g DW in reported *Ulva* examples	Antioxidant, metabolic regulation	Poor aqueous dispersibility and susceptibility to oxidation/light; formulation protection may be required	[49]
Chlorophylls	Photosynthetic pigments	Green seaweeds (*Ulva* spp.)	Total chlorophyll ~3.5–35.4 mg/g DW in reported *Ulva* samples	Antioxidant; natural colorant	Color stability is sensitive to pH, heat and light; may alter beverage appearance	[50]-[52]
Sterols (e.g., fucosterol)	Phytosterols	Brown seaweeds	662–2320 μg/g DW total sterols in brown seaweeds; fucosterol accounted for 83–97%	Cholesterol-related and anti-inflammatory potential	Lipophilic; poor aqueous dispersibility; may require emulsification/encapsulation	[53]-[55]
Omega-3 fatty acids (EPA, DHA)	Polyunsaturated fatty acids	Brown and red seaweeds	EPA reported at ~0.47–42.4% of total fatty acids depending on species; DHA generally lower	Cardiometabolic health	Lipid oxidation and poor aqueous dispersibility; emulsification and oxygen/light control may be necessary	[56]-[58]
Vitamin C	Micronutrients	Various macroalgae	Vitamin C: mean 0.773 mg/g DW; 90th percentile 2.06 mg/g DW	Antioxidant activity, collagen synthesis, and iron metabolism	Heat, oxygen and light can cause losses during processing/storage; bioavailability depends on matrix	[59], [60]
Minerals (iodine, Fe, Ca, Mg)	Inorganic micronutrients	Various macroalgae	Iodine: ~33–391 μg/g DW in selected edible seaweeds; some brown seaweeds may reach 2,500–10,000 μg/g DW	Thyroid, bone and metabolic functions	Requires species-specific dosage control; excessive iodine can create safety concerns	[61], [62]

Fermentation and other processing technologies are an area of increasing interest as they can be used to enhance the nutritional, functional, and/or sensory properties of seaweed-based beverages. Fermentation increases the bioactive compound availability, enhances flavor profiles, and provides for probiotic function [74]. In general, most studies have focused more on the positive nutritional and functional aspects of seaweed processing, while little attention has been given to contaminant behaviour, iodine bioavailability, or overall product safety. Arsenic, cadmium, iodine and *Salmonella* were identified as relevant food safety hazards associated with seaweeds in the European seaweed chain. The presence and concentration of these hazards may depend on the seaweed species, physiological state, harvest/cultivation environment, geographical area and any post-harvest processing [92].

Iodine and contaminant levels can change significantly through processing; for instance, rehydration and boiling decrease iodine content, but still potentially high iodine contents persist after such processing in some varieties of seaweed [93], [94]. Additionally, iodine bioavailability from brown algae is typically high (31% to 90% in vivo), but processing can lead to significant reductions, with the degree of loss being dependent on both iodine speciation and processing conditions [95]. Nevertheless, the effects of processing on the bioavailability of residual iodine remain poorly understood. Future research should therefore optimize processing conditions to enhance functionality while controlling iodine exposure, contaminants, and other food safety risks in seaweed-based foods and beverages.

The regulatory environment makes a safety valuation even more difficult. While EFSA and other regulatory bodies have set maximum tolerable limits for individual contaminants in foods, guidance specific to seaweed-derived beverages is sparse or applied from larger food categories [90]. This kind of regulatory uncertainty highlights the necessity to integrate safety assessment in product development rather than relegating it to a distinct phase of activity after initial design completion.

In conclusion, future studies should use a multi-disciplinary approach that incorporates aspects of nutritional assessment, functional characterization, exposure assessment and monitoring of contaminants and regulatory compliance (Table 3). An integrated framework will be essential to make seaweed-based beverages both functional food products with proven efficacy and safe long-term edible products.

Recognizing the potential of seaweeds as a sustainable food source, FAO has identified the need for harmonised safety standards related to iodine and contaminant exposure in foods derived from

Table 2: Multisensory cues, functional relevance, and evaluation approaches in seaweed-based beverage research.

Multisensory cue	Functional relevance in beverages	Primary sensory challenge in seaweed-based drinks	Common evaluation methods	Mitigation strategies	Refs
Aroma	Drives first impression, expectation formation, and perceived freshness	Marine, iodine-like, and sulfurous notes from brown seaweeds	Descriptive sensory analysis; GC–MS coupled with sensory profiling; consumer aroma liking tests	LAB fermentation; deodorization; aroma/flavor masking; encapsulation of desirable aroma compounds; complementary flavor blending	[74], [78], [79]
Taste	Determines acceptance and repeat consumption	Bitterness and astringency from phenolics and phlorotannins; umami dominance	Hedonic rating; JAR; taste masking studies	Fermentation; bitterness masking; sweetener–acid optimization; flavor blending; reduction of bitter compounds	[80]-[82]
Mouthfeel	Influences drinkability, satiety perception, and quality	Excessive viscosity or slimy sensation due to polysaccharides (alginate, carrageenan)	Texture profile analysis; sensory mouthfeel descriptors; rheology–sensory correlation	Hydrocolloid concentration optimization; enzymatic treatment; filtration/clarification; homogenization; total-solids adjustment	[83], [84]
Aftertaste	Affects lingering acceptance and willingness to repurchase	Persistent marine or bitter aftertaste	Time–intensity analysis; TDS	Fermentation; bitterness masking; flavor balancing; reduction of bitter compounds; formulation optimization	[77], [78]
Visual appearance	Shapes perceived quality, healthfulness, and naturalness	Green–brown coloration; turbidity and sedimentation	Colorimetric analysis (CIELab); visual liking; expectation–disconfirmation tests	Clarification; filtration; homogenization; color optimization; pigment encapsulation; sedimentation stabilization	[51], [85]
Overall sensory integration	Determines holistic product acceptance	Imbalance between health perception and sensory pleasure	Multivariate preference mapping; consumer segmentation	Consumer-driven formulation optimization; multisensory optimization; preference mapping; consumer segmentation; iterative reformulation	[85]-[87]

seaweeds [108]. However, there is still an insufficient integration of regulatory and safety considerations during the development and assessment of beverages containing seaweed. Recent research has given special emphasis to the nutritional composition, bioactive compounds and functional properties; however, issues concerning regulatory compliance, consumer exposure assessment and risk management have attracted relatively less attention.

This imbalance indicates an important gap in the literature. Since different seaweed-based beverages are increasingly developed as novel functional food products, it is important to ensure that product development corresponds with relevant regulatory frameworks and safety requirements. Going forward, it will be critical in future research to include safety assessment, evaluation of exposure and regulatory components that could support consumer protection, support market acceptance and ensure sustainable commercialization of seaweed-based beverages.

Integrating functional efficacy, consumer acceptance, and product safety is essential for the successful commercialization of seaweed-based beverages. Bioactive compounds such as polysaccharides, carotenoids, phenolics, vitamins, and minerals provide antioxidant, anti-inflammatory, prebiotic, and metabolic benefits, but may also affect sensory attributes. Therefore, formulation and processing should balance functionality, sensory quality, iodine and contaminant levels, microbiological safety, and regulatory compliance to support sustainable commercialization. In order to provide a background for these findings, Table 3 summarizes the frequently used safety assessment assays of potential risk and overall safety of seaweed-based beverages.

Table 3 : Common safety assessment assays applied in seaweed-based beverage research (Part 1).

Safety assessment	Principle	What it measures	Quantitative evidence/example	Analytical methods	Refs
Total iodine determination	Quantification of total iodine present in seaweed or seaweed-derived ingredients	Total iodine concentration and potential dietary iodine exposure	Ten edible seaweed species contained 33–391 µg I/g dry weight. *Ulva rigida* contained 33 ± 3 µg/g, whereas *Osmundea pinnatifida*, *Fucus vesiculosus*, and *Bifurcaria bifurcata* contained 302 ± 26, 352 ± 21, and 391 ± 24 µg/g, respectively.	Microwave-assisted extraction using aqua regia followed by ICP-AES	[62]
Iodine quantification and speciation	Differentiation between inorganic and organic iodine species	Total iodine exposure, iodine speciation, bioaccessibility/bioavailability, and potential thyroid-related risk	In a human intervention study, kombu provided 993 and 1,735 µg iodine, with approximately 50.9–55.0% present as inorganic iodide. Estimated iodine bioavailability was 29.5% and 23.7% from kombu compared with 83.5% and 63.7% from equivalent KI interventions.	LC-ICP-MS; urinary iodine analysis	[96], [97]
Heavy metal quantification (As, Cd, Pb, Hg)	Measurement of toxic element concentrations	Exposure to potentially toxic elements and compliance with food-safety limits	Seaweeds from 43 locations. Cd exceeded international limits at all sites, while Pb exceeded international limits at three sites. Total Hg exceeded 0.1 mg/kg DW in 15% of *F. distichus* and 78% of *N. luetkeana* samples.	Elemental analysis of As, Cd, Pb, and Hg	[98]

Table 3 : Common safety assessment assays applied in seaweed-based beverage research (Part 2).

Safety assessment	Principle	What it measures	Quantitative evidence/example	Analytical methods	Refs
Arsenic speciation	Separation and quantification of inorganic and organic arsenic species	Differentiation of toxic inorganic arsenic (As (III) and As (V)) from organic arsenic species	D'Amore et al., reported LOQs of 0.075, 0.241, 0.235, and 0.321 µg/kg for iAs, MMA, DMA, and arsenobetaine, respectively. Lai et al., reported that hijiki (*Sargassum fusiforme*) exceeded the applicable maximum limit for iAs.	HPLC–ICP-MS	[99], [100]
Processing impact assessment	Evaluation of changes in iodine and elemental contaminants following processing	Effect of processing on contaminant concentrations and safety trade-offs	Thermal processing, washing, soaking, blanching, and rehydration can alter or reduce certain elemental contaminants.	Pre–post processing comparison using ICP-MS/elemental analysis	[101], [102]
In vitro bioaccessibility (INFOGEST)	Sequential simulation of oral, gastric, and intestinal digestion	Release and potential bioaccessibility of nutrients, bioactive compounds, and other food components	Brodkorb et al., established the standardized INFOGEST 2.0 static digestion protocol covering oral, gastric, and intestinal phases.	INFOGEST 2.0 followed by compound-specific analysis	[103]
In vitro bioaccessibility (INFOGEST)	Sequential simulation of oral, gastric, and intestinal digestion	Release and potential bioaccessibility of nutrients, bioactive compounds, and other food components	Brodkorb et al., established the standardized INFOGEST 2.0 static digestion protocol covering oral, gastric, and intestinal phases.	INFOGEST 2.0 followed by compound-specific analysis	[103]
Microbiological safety testing	Detection and enumeration of pathogenic, indicator, and spoilage microorganisms	Microbial load, presence of foodborne pathogens, and microbiological safety of seaweed products	Løvdal et al., reviewed reported viable bacterial loads reaching approximately log 7 CFU/g in seaweed. Major hazards included *Bacillus* spp., *Vibrio* spp., and *Aeromonas* spp., while *Salmonella*, *E. coli*, *S. aureus*, and *L. monocytogenes* were also identified as potential concerns.	Plate counting/culture-based enumeration; pathogen detection and microbiological indicator testing	[104]
Cytotoxicity assays	Assessment of cell viability following exposure to seaweed-derived compounds or extracts	Preliminary cellular toxicity and biological effects	Malhão et al., found that fucosterol showed cytotoxic effects against breast cancer cell lines at 2.5–10 µM. Gunasekaran et al., reported cytotoxic activity of *Sargassum wightii* extract against Hep3B cells, with a CTC50 of 180.65 ± 2.87 µg/mL. Therefore, cytotoxicity assays should be regarded as an initial screening approach rather than a standalone indicator of the safety of seaweed-based beverages.	MTT cell-viability assay	[105], [106]

Table 3: Common safety assessment assays applied in seaweed-based beverage research (Part 3).

Safety assessment	Principle	What it measures	Quantitative evidence/example	Analytical methods	Refs
Risk characterization modeling	Estimation of dietary exposure and health risk relative to toxicological reference values	Non-carcinogenic and carcinogenic risks associated with exposure to seaweed-derived contaminants	EFSA et al., estimated that seaweed consumption contributed approximately 10–30% of previous whole-diet exposure to iAs and Pb among adult consumers. Peng et al., found considerable non-carcinogenic and carcinogenic risks from consumption of *Sargassum oligocystum* and *S. polycystum*.	Dietary exposure assessment; EDI, HQ/HI, carcinogenic risk, and Monte Carlo simulation	[90], [107]

4 Research Gaps and Future Directions in Seaweed-Based Beverage Research

Despite growing research on seaweed-based beverages, significant gaps remain in their translational and industrial development. Current studies often focus on bioactivity without integrating functionality, sensory quality, safety, and realistic consumption patterns. Future research should adopt an interdisciplinary approach that incorporates sensory and consumer preferences, iodine and contaminant assessment, processing effects, dietary exposure, and stronger clinical, *in vivo*, and translational evidence, currently suggests an early-to-intermediate stage of fiel.

5 Conclusion

This bibliometric review shows growing global interest in seaweed-based beverages as functional and sustainable products. However, research remains fragmented, focusing mainly on bioactivity while giving limited attention to sensory quality, consumer acceptance, and safety, particularly iodine exposure. These gaps highlight the need for integrated research frameworks linking functionality, sensory quality, safety, and regulatory considerations to support commercial development.

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Authorship contribution

Ria Amelia: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Tia Erfianti: Methodology, Validation, Writing – review & editing. Dedy Kurnianto, Einstivina Nuryadani & DED Setyono: Data curation, Software, Formal analysis & Visualization. Yusuf Andriana: Investigation, Resources, Writing – review & editing. Ratih Pangestuti: Supervision, Project administration, Funding acquisition, Writing – review & editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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