



Chemical Characterization and Potential Industrial Valorization of Brewers' By-Products and *Sargassum fluitans* in Benin with a Focus on Their Potential in a Circular Food Economy Framework

Jean-Claude S. Dossa^{1,2} · Casimir D. Akpovi² · Aurore Richel¹

Received: 6 March 2026 / Accepted: 5 August 2026
© The Author(s), under exclusive licence to Springer Nature B.V. 2026

Abstract

Purpose This study aimed to characterize brewers' spent grain (BSG) and *Sargassum fluitans* III (SfIII) from the Beninese coast and to evaluate their potential as sustainable feedstocks for multifunctional industrial applications. The research addresses the lack of high-value valorization routes for these abundant biomasses in West Africa, aligning with circular-economy principles.

Methods Both biomasses were collected during representative production and seasonal stranding periods and underwent comprehensive profiling, including proximate composition analysis, fatty acid characterization by GC-FID, and secondary metabolite identification by UPLC-QTOF-MS. Antioxidant potential was assessed by measuring total phenolic content (Folin-Ciocalteu), and safety was evaluated by quantifying heavy metals, specifically arsenic and mercury.

Results BSG showed high protein (27–34%) and carbohydrate (47–53%) contents, with lipids (up to 7%) dominated by linoleic (C18:2), palmitic (C16:0), and oleic (C18:1) acids. SfIII was characterized by high mineral content (18–41%) and 12% carbohydrates. UPLC-QTOF-MS identified diverse phospholipids, phytosterols, and flavonoids, confirming significant bioactive potential. Crucially, arsenic and mercury levels remained at trace concentrations, supporting the safety of these materials for further processing.

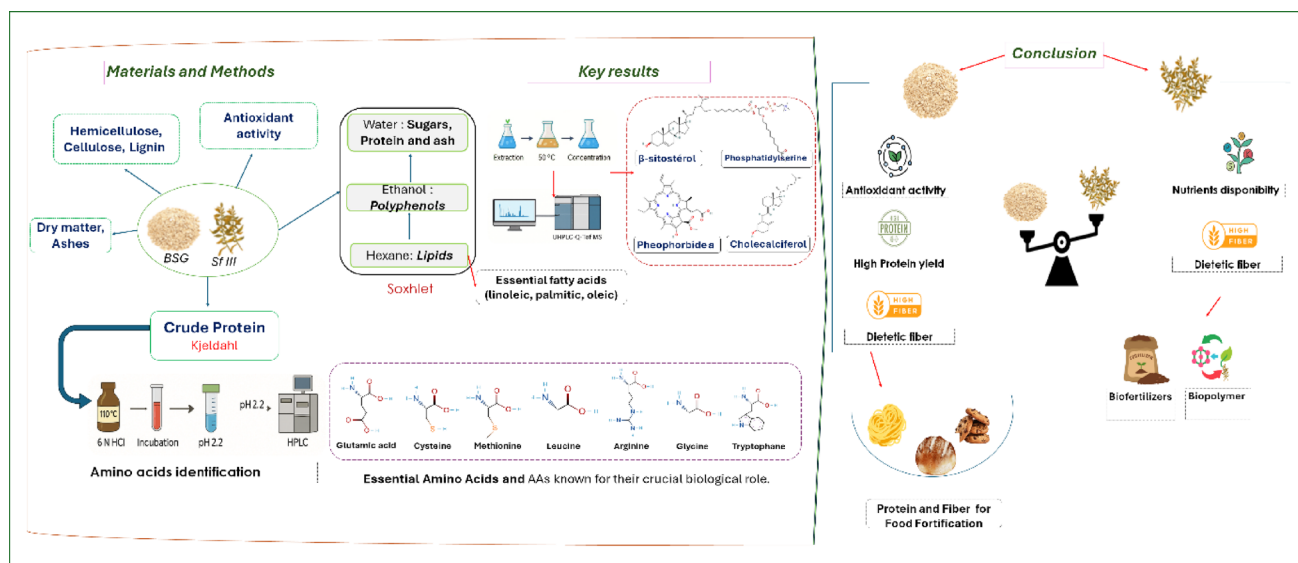
Conclusion The results demonstrate that BSG and SfIII are viable candidates for nutrient-dense food ingredients, cosmetic antioxidants, and bio-based materials. This study provides a scientific baseline to strengthen local value chains in Benin and support sustainable economic development by valorizing underutilized biological resources.

✉ Jean-Claude S. Dossa
sjcdossa@uliege.be

¹ Laboratory of Biomass and Green Technologies, University of Liege, Gembloux Agro-Bio Tech Campus, Gembloux, Belgium

² Non-Communicable Diseases and Cancer Research Unit, Laboratory of Applied Biology Research, Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, Abomey-Calavi, Benin

Graphical Abstract



Highlights

- Unlocking the value of Benin's BSG and *Sargassum* through chemical profiling.
- UPLC-QTOF-MS reveals bioactive phospholipids and potent natural antioxidants.
- Brewery by-products yield up to 34% protein for nutrient-dense ingredients.
- Rigorous As and Hg screening validates safety for industrial re-utilisation
- Strategic circular economy roadmap for sustainable resource management

Keywords Brewers' spent grain · Pelagic *Sargassum* · Food ingredients · Bioactive compounds · UPLC-QTOF-MS profiling · Sustainable food systems

Introduction

The increasing awareness of the interconnections between food production, global population growth, human health, and climate change has intensified interest in the search for alternative and sustainable sources of bioactive molecules. In this context, particular attention is now being given to the use of underexploited organic residues, including industrial and agri-food by-products and algal biomass, as promising raw materials. These resources are of special interest because they do not compete for arable land, are often poorly valorized, and represent a largely untapped potential for innovation and sustainable value creation. Globally, the pursuit of environmentally responsible technologies [1] has led to an increasing recognition of such feedstocks as valuable sources of bioactive compounds [2]. The recovery of biomolecules (such as phytochemicals, vitamins, lipids, and proteins) from these materials is now seen as an economically viable and ecologically sound approach to promoting circular bioeconomy principles [3]. In regions such as Africa, where large quantities of organic residues remain underutilized, these biomasses could offer unique

opportunities to foster local value chains, enhance awareness of circular economy concepts, and strengthen the development of a sustainable bioeconomy.

This study focuses on Benin, where two underexploited organic material streams are attracting growing interest, namely beer production residues and seaweeds that proliferate along the coastline. Both streams currently pose significant management and sanitation challenges. Their local availability at the point of generation also provides an opportunity to investigate biomass resources that can be recovered and valorized within regional circular bioeconomy systems. They are generally redirected toward low-value applications such as animal feed, composting, or construction materials. Although these pathways contribute to biomass recovery and waste reduction, their wider implementation remains constrained by practical and compositional limitations, including the high moisture content and perishability of brewery spent grain [4, 5], as well as the high ash and salt contents and the presence of potentially toxic elements in stranded *Sargassum* [6, 7]. For instance, one ton of dried brewery spent grains can provide approximately 600 kg of livestock feed [5, 8]. Similarly, Speede et al. [9] reported

that one ton of fresh *Sargassum* can provide enough seaweed supplement to sustain around one hundred sheep for a week. In several African contexts, additional uses of seaweed have been reported, particularly in the construction sector, where they may be incorporated into the fabrication of building blocks for domestic purposes [10–12]. Unlocking the potential of these materials for higher-value applications, particularly in fields related to human nutrition and health, requires a thorough understanding of their chemical composition. This study is therefore dedicated to the comprehensive characterization of these biomasses as a foundation for their valorization within a sustainable and circular bioeconomy framework.

When examining brewery residues, it is important to note that beer is the fifth most consumed beverage in the world [13]. In 2023, global beer production reached 1.89 billion hectoliters (hL), representing a 1.3% increase compared with the previous year, corresponding to an additional 25 million hL produced worldwide. Africa recorded the highest proportional growth among continents, with production increasing by 6.6 million hL relative to previous years [14]. Beer production generates substantial residues, particularly brewers' spent grains (BSG), which account for approximately 85% of the total secondary flows generated [15]. Global BSG production amounts to 38–40 million tonnes annually [16], equating to roughly 20 kg per hectoliter of beer. In Benin, where annual beer production has remained around 1.3 million hL since 2021, approximately 26,200 tonnes of BSG are produced each year. Due to its high moisture content, preservation of BSG in Benin is challenging, and surplus material is predominantly used as animal feed or disposed of [17]. Landfill disposal is specifically concerning, as each tonne of BSG releases an estimated 513 kg of CO₂ equivalent, contributing to greenhouse gas emissions [13].

Turning to algae, it is worth noting that since the early 2000s, blooms and invasions of marine macroalgae, particularly *Sargassum* spp., have intensified worldwide. These events have had substantial ecological, social, and economic repercussions, affecting marine ecosystems, fisheries, tourism, and coastal communities [18–21]. Over the past decade, about 29% of the world's coastlines have experienced stress from algal blooms, predominantly caused by three morphotypes: *Sargassum natans* I, *Sargassum natans* VIII, and *Sargassum fluitans* III, the latter being the most widespread [22, 23]. In 2019, the area affected by *Sargassum* blooms was estimated at 8850 km², with over 20 million tonnes floating across the surface of the tropical Atlantic, from Central America to West Africa [21, 22]. The decomposition of *Sargassum* releases toxic gases, in particular hydrogen sulfide (H₂S), which degrade air quality and can induce acute toxicological effects on the nervous

and respiratory systems [19]. In Benin, recurrent influxes of *Sargassum fluitans* along the southern coastline create serious challenges for fisheries and coastal communities. These occurrences may be linked to shifts in ocean circulation patterns, increased nutrient inputs from rivers and agricultural runoff, and the effects of climate change, such as warming sea surface temperatures that favor the proliferation and transport of pelagic *Sargassum* across the Atlantic [24].

Although BSG and pelagic *Sargassum* have been widely characterized in North and South America, the Americas, and Asia, detailed data on their composition [6, 8, 25], inter-annual variability, and safety constraints in African settings remain scarce, despite rapidly growing brewing activities and coastal biomass accumulations. In West Africa, several studies have reported increasing quantities of organic and agro-industrial residues resulting from urbanization, agricultural intensification, and food-processing activities, while also emphasizing their potential for agricultural and energy recovery [26–31]. However, the available literature remains limited concerning the physicochemical characterization of locally available biomass resources. As a result, the assessment of their suitability for specific valorization processes is often based on data generated under different environmental and production conditions. This lack of locally derived information also restricts the development of waste management and biomass utilization strategies adapted to regional realities. Within this context, the characterization of Beninese BSG and *Sargassum fluitans* III over two consecutive years (2023 and 2024) provides new compositional data for two biomass resources that remain poorly documented in West Africa. These sampling periods were selected to encompass major seasonal *Sargassum* influx events observed along the Beninese coast, while repeated BSG collections during the same period allowed the characterization of brewery residues generated under local production conditions. Comparison of the obtained results with those reported in the international literature also allows an assessment of their compositional characteristics and potential suitability for different valorization options, while providing a scientific basis for future biomass management and bioresource utilization strategies adapted to regional conditions.

Materials and Methods

Description of the Study Sites, Field Collection, and Sample Preparation

BSG was collected at the local SOBEBRA brewery in Cotonou during several collection campaigns (between 2023 and 2024). BSG was dried at 40 °C for three days, followed by

grinding to a particle size of 0.5 mm using a Fritsch Pulverisette 19 knife mill. The resulting spent grains were then recovered and stored in polyethylene bags at room temperature for subsequent analyses.

The *Sargassum* biomass was manually collected from three coastal sites near Cotonou and Ouidah (Benin) during two major invasion events, in August–September 2023 and April 2024 (Fig. 1). These periods were selected because they correspond to the two main seasonal *Sargassum* influxes observed along the Beninese coast. Samples from the three sites were pooled within each campaign to obtain a representative biomass for valorization purposes rather than to evaluate site-specific variability. After rinsing with tap water followed by distilled water, the biomass was sorted into morphotypes according to published identification criteria [32, 33]. *Sargassum fluitans* III (SfIII) was visually identified as the dominant morphotype during both campaigns. Its recurrent dominance over other morphotypes in several areas of the Tropical Atlantic [22, 32, 34] supports the selection of *S. fluitans* III as the target morphotype for the present characterization. The biomass was then air-dried at room temperature for approximately seven days, ground

into powder, and stored in airtight containers protected from light and moisture until analysis.

Physicochemical Analysis of Raw Materials

Unless otherwise stated, all analytical standards were purchased from Sigma-Aldrich (St. Louis, MO, USA). Solvents and analytical reagents, including ethanol, methanol, Folin-Ciocalteu reagent, and Titrisol® sulfuric acid solutions, were obtained from Merck (Darmstadt, Germany). All chemicals were of analytical grade and used without further purification.

The moisture content of the samples was determined gravimetrically after treatment in a Memmert SNB100 furnace at 105 °C, while ash content was measured gravimetrically after treatment in a muffle furnace at 550 °C, following the procedures outlined in AOAC (2000). Extractable compounds were quantified using the Soxhlet method, following the NREL protocol described by Sluiter et al. [35]. Extractions were performed in three successive stages, each lasting 6 h, using distilled water and ethanol (97%, v/v). Lipid content was determined gravimetrically using the same procedure, with hexane employed as the extraction solvent.

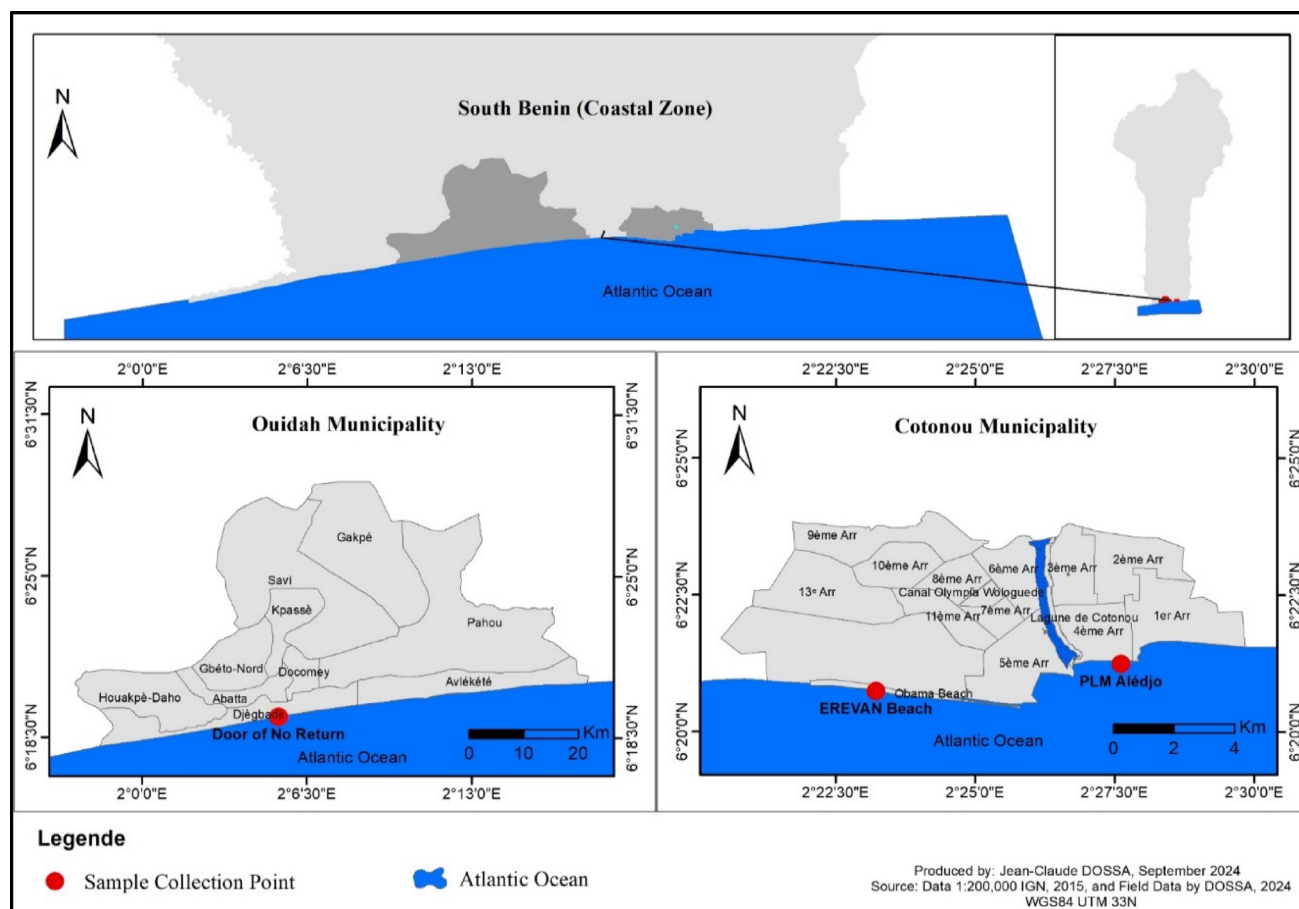


Fig. 1 Location of *Sargassum* brown algae sampling sites during the 2023–2024 *Sargassum* flood in Benin

The cellulose and hemicellulose contents were determined by quantifying their respective monosaccharides, namely glucose for cellulose, and arabinose, xylose, rhamnose, mannose, and galactose for hemicellulose. Practically, acid hydrolysis (1 M H_2SO_4) was performed on 25–50 mg of each dried biomass sample. After hydrolysis (3 and 6 h, respectively, for hemicellulose and cellulose), the reaction medium was neutralized using 1 mL of 15 M NH_4OH , and 1 mL of 98% 2-deoxy-D-glucose was added as internal standard. The released sugars were reduced in the presence of sodium borohydride (NaBH_4) and then derivatised to alditol acetate using acetic anhydride, as described by Blakenely et al. [36]. Quantification was performed by gas chromatography using an Agilent chromatograph (7890B series) equipped with a flame ionization detector. A high-performance HP1 methylsiloxane capillary column (30 m, 0.32 mm, 0.25 μm) was used to separate the components. Data were analyzed using Lab ChemStation software [37].

The crude protein content was determined using a nitrogen conversion factor of 6.25, following the Kjeldahl method described by Ortiz et al. [38]. In summary, 100 mg of the ground and dried sample was mineralized with concentrated H_2SO_4 (95%) and a CTQ catalyst (1.5 g $\text{K}_2\text{SO}_4 + 0.045$ g $\text{CuSO}_4 \cdot 0.5\text{H}_2\text{O} + 0.045$ g TiO_2) using a Tecator 105 heater at 360 °C for 2 h, supplied by FOSS Benelux. Subsequently, the sample was titrated with a 0.01 M H_2SO_4 solution using a FOSS Benelux Kjeltac 2300. Amino acid assay and identification were conducted following the methodology of Siow and Gan [39], with certain modifications. Briefly, a sample was mixed with 10 mL of 6N HCl containing 0.1% (w/v) phenol, purged with nitrogen, and hydrolyzed at 110 °C for 24 h. The hydrolysate was then adjusted to pH 2.2 using 1N NaOH, after which 1 mL of norleucine solution (50 μM) prepared in citrate buffer at pH 2.2 was added as an internal standard. Amino acid quantification was performed using the Stein and Moore HPLC method, with 20 μL of the prepared sample injected for analysis.

The lipid content and total fatty acids profile (free+mono-, di-, triglycerides) were determined from the hexane-extracted samples. Total lipids were measured gravimetrically, while the total fatty acids profile was evaluated after derivatization to fatty acid methyl esters using boron trifluoride-methanol reagent (methanol/ BF_3 /hexane, 55:25:20, v/v/v) by esterification/transesterification [40]. Quantification was conducted by GC-FID using heptadecanoic acid (C17:0) as the internal standard. The fatty acids were identified by comparing their retention times to a reference standard (Supelco 37 Component FAME Mix), which contains 37 fatty acid methyl esters (C4–C24). The internal standard was employed to determine the response factor of each FAME in the reference standard for quantification.

Metal concentrations (Cd, Cu, Pb, Zn, Hg, and As) were quantified by atomic absorption spectrometry (AAS) following the AOAC Official Method 999.11 [41]. Analytical measurements were performed using several PerkinElmer instruments, including a PinAAcle 900T (Cd, Pb, As), an FMS 400 Mercury Analysis System (Hg), and an Analyst 200 (Cu, Zn). Metal concentrations were expressed as milligrams per kilogram (mg/kg) of dry biomass.

Polyphenols were extracted from the biomass using 70% ethanol (v/v) at a biomass-to-solvent ratio of 1:20 (w/v) at 50 °C for 3 h. The resulting extracts BSG and SfIII were analysed using an ultra-high-performance liquid chromatography system (UHPLC, Shimadzu Nexera) coupled with a Q-ToF X-500R mass spectrometer (AB Sciex), following the method of Man et al. [42]. Chromatographic separation was performed on a Phenomenex Kinetex biphenyl column (2.6 μm , 100 $\times$ 2.1 mm) maintained at 40 °C. The mobile phase consisted of ULC-MS grade water with 0.1% (v/v) formic acid (solvent A) and methanol (solvent B), delivered at 0.3 mL min^{-1} under the following gradient: 98% A to 2% A over 0–14 min, held to 17.5 min, and returned to initial conditions by 19.1 min. In negative ionization mode, solvent A was modified to 2 mM ammonium acetate with 0.2% (v/v) formic acid, and solvent B was replaced by acetonitrile. Samples (0.5 μL) were analyzed in both positive and negative electrospray ionization (ESI) modes, with gas and sheath gas temperatures of 320 °C and 325 °C, and capillary voltages of 30 kV and 35 kV, respectively. Compound identification was based on UPLC-Q-ToF MS/MS data processed in MZmine and annotated via molecular networking using the GNPS platform.

Total polyphenol (TPC), flavonoid (TFC), and condensed tannin (CTC) contents in the ethanolic extracts were determined spectrophotometrically after dissolution of 10 mg of each dry crude extract in 1 mL of water corresponding to 10 mg mL^{-1} (w/v).

TPC was determined using the Folin-Ciocalteu method, following the methodology outlined by Singleton et al. [43], with minor modifications. A volume of 125 μL of each extract was combined with 625 μL of Folin-Ciocalteu reagent and 4.75 mL of distilled water. Following a 5 min incubation period, 500 μL of sodium carbonate (Na_2CO_3) solution (75 mg/mL, W/v) was added. The absorbances of the extracts were determined at a fixed wavelength of 760 nm using a spectrophotometer. Gallic acid was used as an external standard. TPC was expressed in mg of gallic acid equivalent (GAE) per g of extract (mg GAE/g).

TFC was measured according to a method adapted from Kim et al. [44]. 500 μL of a 2% (W/v) aluminium trichloride (AlCl_3) solution was combined with 500 μL of the extract and 3 mL of distilled water. The absorbances were measured at 415 nm using a spectrophotometer. Quercetin was

used as an external reference. The total flavonoid contents were expressed in mg of quercetin equivalent (QE) per g of extract (mg QE/g).

CTC was measured using the method described by Heimler et al. [45]. A 50 μ L volume of extract was mixed with 1.5 mL vanillin solution (4%, W/v) and 750 μ L of fuming hydrochloric acid. Subsequently, the absorbance was measured at 500 nm, using catechin as the reference standard. CTC was expressed in mg of catechin equivalent (CE) per g of extract (mg CE/g).

Determination of the Antioxidant Activity

The antioxidant activity of ethanolic extracts from BSG and SfIII was evaluated using two complementary assays.

Ferric Reducing Antioxidant Power (FRAP) Assay

The ferric (Fe^{3+}) ion reducing capacity, which measured the extracts' electron-donating capacity, was assessed following the methodology proposed by Ouattara et al. [46], with minor modifications. Briefly, an aliquot of 100 μ L of each extract was mixed with 2850 μ L of freshly prepared FRAP reagent. This reagent consisted of 1 mL of 10 mM 2,4,6-tripyridyl-5-triazine (TPTZ) dissolved in 40 mM HCl, 1.0 mL of 20 mM $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, and 10 mL of 300 mM sodium acetate buffer adjusted to pH 3.6. The resulting reaction mixture was kept at a temperature of 37 °C and incubated in the dark for 30 min. Subsequently, the absorbance of the Fe^{2+} -TPTZ complex was measured spectrophotometrically at 593 nm. The antioxidant capacity of each extract was quantified based on a calibration curve made using Trolox. FRAP values were expressed in μ mol of Trolox equivalent (TE) per g of dry extract (μ mol TE/g).

DPPH Radical Scavenging Assay

The capacity of various biomasses to scavenge the free radical 2,2-diphenyl-1-picrylhydrazyl (DPPH) was quantified by the method published by Trigui et al. [47]. 50 μ L of each extract was added to 2 mL of 4% (m/v) methanolic DPPH solution. After 30 min, the absorbance of the reaction mixture was measured at 517 nm, and the antioxidant activity was expressed as a percentage of the DPPH radical scavenging capacity (%DPPHsc), calculated using the following formula:

$$\text{DPPHsc}(\%) = \frac{A_s - A_c}{A_c} \times 100$$

where A_s is the absorbance of the sample at $t=30$ min, and A_c is the absorbance of the control, consisting of the DPPH

solution with 50 μ L of the solvent used for the extracts but without any extract, to measure the maximum absorbance of unreacted DPPH.

Data Treatment and Statistical Analyses

All experiments were performed in triplicate. A t-test was conducted to compare groups with normally distributed variables after a Shapiro–Wilk test. For variables that did not follow a normal distribution, the Mann–Whitney U test was applied. All statistical analyses were performed using R software, and figures were made in GraphPad Prism 8.

Results and Discussion

Primary Metabolite Composition

The successful valorization of biomass depends on a detailed understanding of its chemical composition [6]. Chemical characterization of brewers' spent grains (BSG) from Benin revealed that they were predominantly composed of hemicellulose (34–39%) and protein (27–34%), with significant variability ($p < 0.005$) in extractives, protein, and hemicellulose content among samples. *S. fluitans* III (SfIII) exhibited a lignocellulosic content ranging from 29 to 56%, ash content between 15 and 42%, and a low lipid fraction (0.4%). The overall composition varied significantly ($p < 0.05$) across sampling periods, particularly in respect to the proportions of extractives, hemicellulose, lignin, and ash (Fig. 2).

The polysaccharide fraction (hemicellulose and cellulose) of BSG from Benin is consistent with the value reported by McCarthy et al. [48], accounting for more than 50% of the dry matter. For SfIII, the polysaccharide content measured was lower than that reported by Alzate-Gaviria et al. [49] for algae collected in Puerto Morelos, Mexico (34%), which reflects the influence of environmental conditions and harvest periods on biomass composition. Such non-standardized composition could affect the subsequent valorization potential of these algae.

The measured lignin content ranged from 4 to 8% in BSG and 8 to 22% in SfIII. The literature reports higher lignin levels in BSG (14–20%), depending on the beer production process and the type of grain used [5, 50, 51]. The lignin content of SfIII from Benin is higher than the 3–4% reported for *S. fluitans* collected in Puerto Morelos, Mexico [49].

The ash content of BSG was lower than previously reported by Ajanaku et al. [52] but consistent with more recent findings (3.6–4.7%) [50, 51, 53]. In contrast, SfIII exhibited a substantially higher ash content (18.5–42%), exceeding the values reported by Oyesiku and Egunyomi [54] and was comparable to those documented by Machado

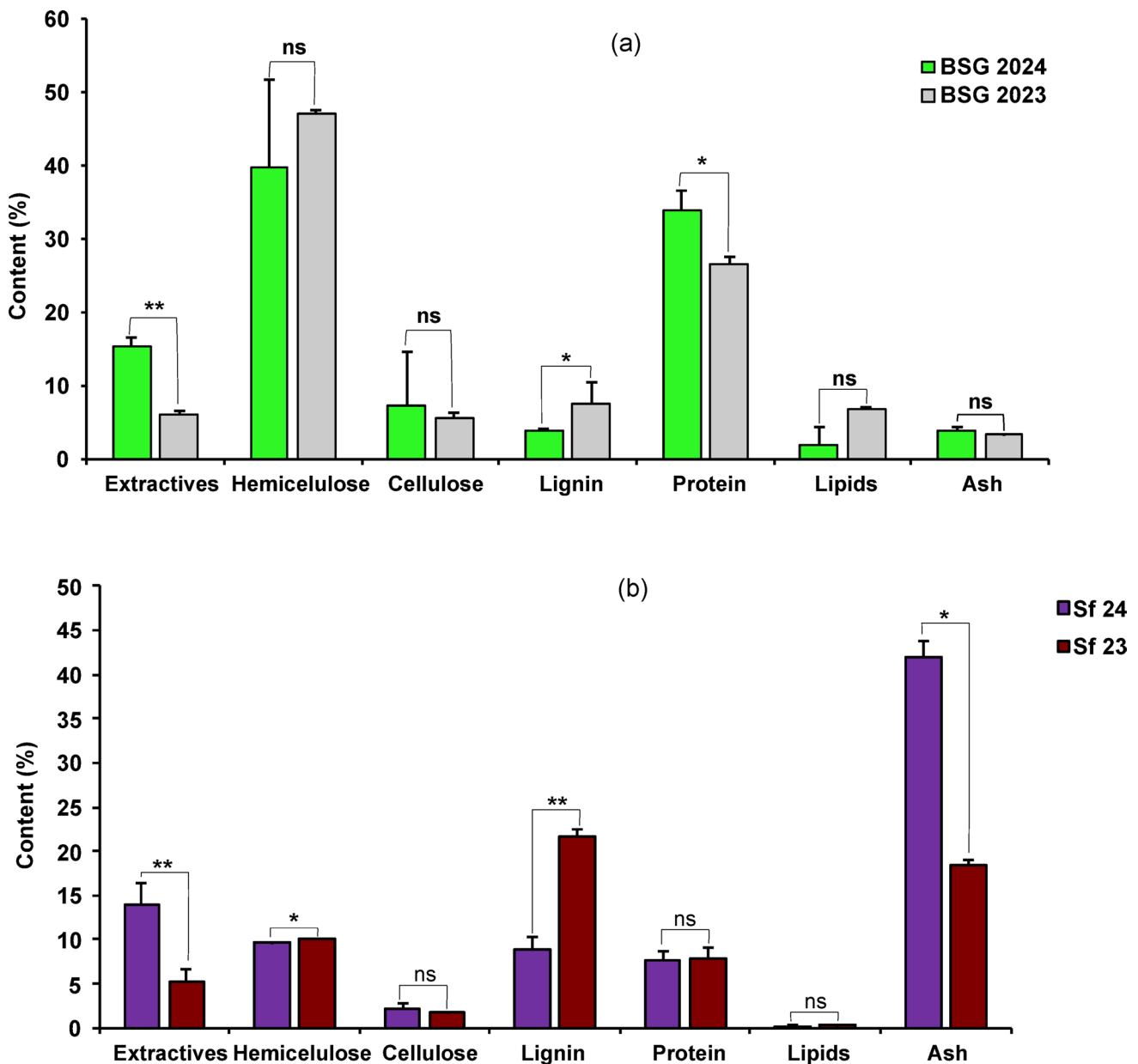


Fig. 2 Comparative chemical composition (per 100 g dry matter basis) of BSG (a) and SfIII (b) collected in 2023 (BSG 2023 and Sf 23) and 2024 (BSG 2024 and Sf 24). Values represent means $\pm$ SD of triplicates. Significance levels: ns (non-significant), * $p < 0.05$, ** $p < 0.01$

et al. [23], Saldarriaga-Hernández et al. [55], and Vázquez-Delfin et al. [56], which ranged from 33.7 to 55.7%, 24–30%, and 18–24%, respectively. The high ash content of algae provides essential trace elements and minerals, offering potential benefits for applications such as soil amendment [57]. However, the combination of elevated ash levels and the capacity of algae to actively and passively accumulate heavy metals [58] may limit the direct use of *Sargassum* biomass in human or animal nutrition.

Extractives content varied significantly in BSG and SfIII, ranging from 6 to 13% and 5–26% on a dry weight basis, respectively, which reflects the presence of non-structural

compounds such as secondary metabolites and free sugars. Mussatto et al. [5] reported that brewers' grains can contain up to 25% extractives, while successive Soxhlet extractions of *Sargassum* with ethyl acetate, acetone, and ethanol yielded a total extractive content of 3.52%, highlighting the influence of solvent polarity, species, origin, and growth stage on extraction efficiency [59].

Lipid analysis revealed distinct profiles for BSG (up to 7%) and *S. fluitans* III (0.4%). The lipid content of BSG is comparable to values reported by Faulds et al. [60] and Khidzir et al. [61] although del Río et al. [62], Forsell et al. [63], and Robertson et al. [64] reported slightly higher

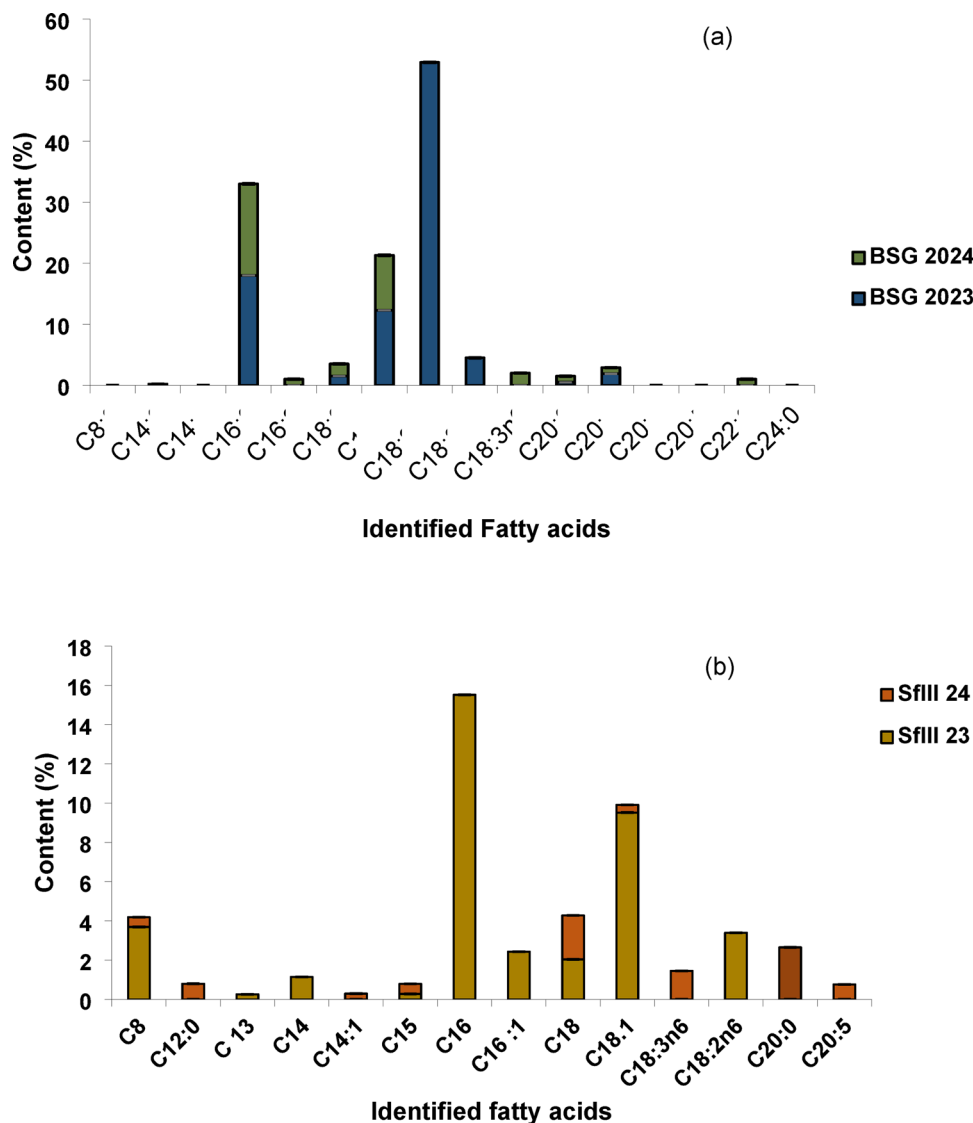
levels (9–10%) in brewers' grains. For *S. fluitans* III, the lipid content aligns with data from Dewinta et al. [65] and Tulashie et al. [66] for *Sargassum* harvested in the Isle of Pane and Ghana, respectively, and is consistent with the typical lipid range of brown algae species (0.5–3.9%) reported by Hardouin et al. [67] and Milledge and Harvey [68].

The fatty acid profiles of BSG exhibited notable differences, with linoleic acid (C18:2), palmitic acid (C16:0), and oleic acid (C18:1) as the predominant fatty acids (Fig. 3a). Our results highlighted, however, that significant differences in the content of both linoleic acid and palmitic acid could be observed as a function of the beer process conditions and year of production. Although the lignocellulosic composition remained relatively stable across batches, the fatty acid profile appeared more susceptible to inter-batch variations. Other fatty acids, including myristic (C14:0), palmitoleic (C16:1), and γ -linolenic (C18:3), were present at low levels (<10%) but also showed inter-batch variations. Trace

amounts of very long-chain fatty acids (C22:0 and C24:0) were also detected but remained negligible. These results are consistent with previous studies reporting high levels of linoleic, palmitic, and oleic acids in brewers' grains [1, 69].

SfIII samples collected in 2023 were dominated by palmitic acid (C16:0) and oleic acid (C18:1). In contrast, samples collected in 2024 exhibited substantially lower levels of these fatty acids, approximately 1% and 4%, respectively (Fig. 3b). Other fatty acids, including C8:0, C12:0, and C18:2, were present at concentrations below 5% in both harvest years, although significant variation was observed. These results are consistent with Ganesan et al. [70], who reported that algal lipids are predominantly composed of saturated fatty acids, particularly palmitic acid. Several studies have reported that palmitic, oleic, and arachidonic acids are the predominant fatty acids in *S. natans* samples from the central North Atlantic Ocean, as well as in *S. fluitans* and *S. natans* collected along the coasts of the Turks

Fig. 3 Fatty acid profile (per 100 g dry matter basis) of BSG (A) SfIII (B) collected in 2023 (BSG 2023 and Sf 23) and 2024 (BSG 2024 and Sf 24). Data represent means $\pm$ SD (n = 3)



and Caicos Islands [23, 57, 71]. A similar fatty acid profile has also been observed in benthic *Sargassum* species [72–74]. These findings suggest a strong convergence in the lipid composition of *Sargassum* species across different habitats (benthic or pelagic), while also highlighting the influence of ecological and environmental factors in driving inter- and intraspecies compositional variability.

Regarding BSG, the crude protein content was high, ranging from 27 to 34% on a dry matter basis. This range corresponds to the upper limit of 18–30% reported by Qin et al. [3] and exceeds the values commonly cited in earlier studies, such as 15–26% reported by Connolly et al. [2], and approximately 20% reported by Mussatto et al. [5]. Differences among studies may reflect variations in biomass origin, processing conditions, and methodological approaches used for protein estimation, including the nitrogen-to-protein conversion factor applied. In contrast, the crude protein content of SfIII was measured at 8%, which falls within the typical range of 3–15% for brown seaweeds [75]. Nevertheless, this value is higher than those reported for *Sargassum* species collected along the north-western Mediterranean coast [76], and in Jamaica [23], indicating that the crude protein content of *Sargassum* is strongly influenced by geographical and environmental factors. As highlighted by [77], variations in protein content among algal species may result from both interspecific differences and intraspecific factors, including developmental stage, seasonal fluctuations, and environmental conditions. It is also important to note that protein content is generally estimated from total nitrogen using a conversion factor (N factor), most commonly 6.25. However, this universal factor may lead to an overestimation of true protein levels, particularly in algae and other non-conventional biomass sources [78].

To facilitate comparison with previous studies, the main compositional characteristics of Beninese BSG and SfIII are summarized alongside representative values reported for similar biomasses from other geographical regions

(Table 1). This comparison highlights the compositional features observed in the present study while placing them within the range of variability reported in the literature.

Overall, both biomasses exhibited compositional characteristics generally consistent with the ranges reported in the literature, while several parameters, notably hemicellulose content in BSG and ash content in SfIII, differed from commonly reported values, emphasizing the importance of local feedstock characterization.

Amino Acid Profile

Amino acid profiling confirmed the presence of all essential amino acids (EAAs) in both BSG and SfIII (Fig. 4). BSG exhibited an amino acid profile dominated by glutamic acid (Glu, 6.21%), leucine (Leu, 3.15%), and proline (Pro, 2.72%). This profile is consistent with previous findings by Coelho et al. [82] and Mussatto et al. [5]. Such a composition is suitable for animal feed formulations but could also offer attractive applications, particularly in the production of bioactive peptides for functional foods.

The amino acid profile of *S. fluitans* III revealed the presence of glutamic acid (Glu, 1%), aspartic acid (Asp, 0.8%), and glycine (Gly, 0.5%). The high contents of Asp and Glu are characteristic features of most macroalgae [83]. All EAAs were detected in SfIII except tryptophan, collectively accounting for approximately 36% of the total amino acid content, consistent with previous reports indicating that EAAs typically represent more than 30% of total amino acids in algae [84]. This amino acid composition suggests that SfIII exhibits an essential amino acid (EAA) profile comparable to those reported for some leguminous crops and soybean, where EAAs typically account for approximately 30–40% of total amino acids [70]. However, the nutritional relevance of this profile should be considered in light of the relatively low crude protein content of SfIII and the presence of inorganic elements that may affect its suitability for food and feed applications. Thus, SfIII may be regarded as a biomass resource containing nutritionally relevant compounds rather than as a primary protein source.

The amino acid score (AAS) evaluates the efficiency of dietary nitrogen utilization by comparing the content of the limiting essential amino acid (EAA) in a protein source with a reference amino acid profile (Table 2). When the composition of Beninese BSG and SfIII is compared with the World Health Organization (WHO) [85] reference pattern for adults (0.66 g protein/kg/day), BSG generally aligns more closely with the recommended profile than *S. fluitans* III.

Both BSG and SfIII exhibited specific EAA deficiencies relative to the WHO reference pattern. The primary limiting EAA in BSG was lysine (Lys, 2.5%), which was found to be substantially lower than the recommended

Table 1 Comparison of the main compositional characteristics of Beninese BSG and *S. fluitans* III with representative values reported in the literature

Parameter (% DM unless otherwise stated)	BSG–Benin	Literature (BSG)	SfIII–Benin	Literature (<i>Sargassum</i> spp.)
Crude protein	27–34	18–28 [5, 79]	8–12	4–12 [55, 75]
Ash	3.6–4.7	3–5 [5]	18.5–42	20–35 [23, 56]
Lipids	4–7	6–10 [5, 62]	0.4	<4 [67]
Acid-insoluble residue	4–8	14–20 [5, 51]	8–22	3–8 [49]
Hemicellulose	34–39	26–30 [5, 8]	–	–
Cellulose	12–16	15–19 [5, 8]	–	–
Total phenolic content (mg GAE g ⁻¹ extract)	1.13	0.35–0.66 [80, 81]	0.80	1.2–2.5 [46, 57]

Fig. 4 Amino acid composition (per 100 g dry matter basis) of BSG (a) and SfIII (b) collected in 2023 (BSG 2023 and Sf 23) and 2024 (BSG 2024 and Sf 24). Values represent means $\pm$ SD of triplicates. Significant differences between sampling years are indicated (* p < 0.05, ** p < 0.01)

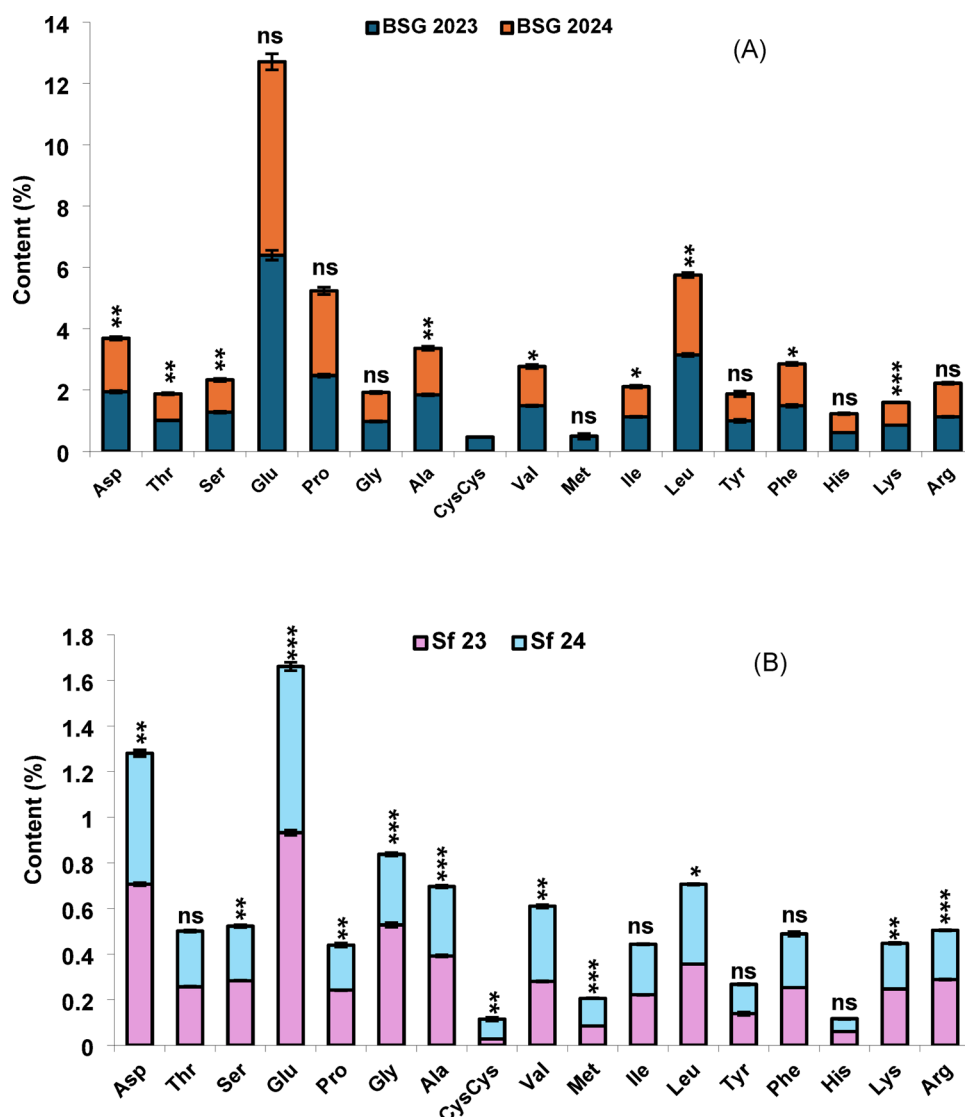


Table 2 Essential amino acid (EAA) composition of BSG and SfIII compared with WHO (2007) adult reference pattern (per 100 g protein)

Amino acid	WHO (g/100 g protein)	BSG (% of total AA)	SfIII (% of total AA)
Threonine	2.3	3.5	4.7
Methionine	1	n.d	1.6
Isoleucine	3	4.0	4.0
Leucine	5.9	10.5	6.5
Phenylalanine+Tyrosine	3	9.1	6.9
Histidine	1.5	5.6	1.2
Lysine	4.5	2.5	4.5
Valine	3.9	5.1	5.2

*n.d.: not detected

4.5%. Conversely, SfIII met the lysine requirement but was slightly deficient in histidine (His, 1.2% vs. 1.5% WHO standard). These differences mainly reflect variations in amino acid balance between the two biomass types rather than the strict nutritional superiority of one over the other.

Secondary Metabolite Composition

The hydroethanolic extracts of BSG and SfIII were found to contain a broad panel of distinct secondary metabolites, including polyphenols (mostly phytosterols and flavonoids), terpenoids (especially triterpenoids), and free lipids (phospholipids and free polyunsaturated fatty acids (PUFAs)) (see also Supplementary Information SI1 and SI2). Both biomasses also contained some ethanol-soluble phospholipids, namely phosphatidylinositols (PI) and phosphatidylethanolamines (PE), which play fundamental roles in maintaining membrane structure, fluidity, and cellular

signaling pathways [86]. Specific molecular species, including PI (18:0/22:4) and PE (18:0/22:1), were detected in both extracts. While these lipid classes are frequently reported in the literature in relation to various bioactivities, including anti-inflammatory and neuroprotective effects [87, 88], the qualitative nature of the present LC–MS detection precludes any assessment of their recoverability or processability. Both BSG and SfIII also contained cholesterol, the polyunsaturated fatty acid linoleic acid, and the flavonoid heptamethoxyflavone.

Interestingly, SfIII was found to contain ergosterol, a compound widely investigated for its biological activities and recognized as a precursor of vitamin D₂. Moreover, it represents a valuable platform molecule for the synthesis of various steroid-based drugs [89, 90]. Benzofuranone was also identified in SfIII, a structural class previously associated in the literature with anti-inflammatory and hepatoprotective properties, although such properties remain strongly dependent on compound isolation and structural context [91, 92].

Analysis of the hydroethanolic extracts of both BSG and SfIII revealed that polyphenols are among the major constituents. In BSG, they accounted for approximately 12% of the total extract weight, whereas their levels were comparatively lower in SfIII (1%). The total polyphenol content (TPC) of BSG reached up to 1.13 mg GAE/g, exceeding values reported by Bonifácio-Lopes et al. [81] (0.66 mg GAE/g), Horn et al. [93] (0.57 mg GAE/g), and Spinelli et al. [80] (0.35±0.01 mg GAE/g). Flavonoid contents were notably high (11.4 mg QE/g), surpassing previously published data [69, 94]. These variations can be largely attributed to differences in extraction conditions, solvent polarity, and the initial composition of the raw material [95]. The condensed tannin content in BSG (0.71 mg CE/g) was slightly lower than previously reported values [93], which may be explained by thermal degradation occurring during industrial processing. Such differences in polyphenol and tannin content are likely to influence the biological activities of the extracts, including their antioxidant and potential health-promoting properties, thereby highlighting the importance of optimizing extraction parameters for functional applications.

The TPC of SfIII (0.8 mg GAE/g) fell within the typical 0.2–2.5% range reported for *Sargassum* species [96], although those values were lower than the ones published by Davis et al. [6] (1.20±0.43 mg GAE/g) and Ouattara et al. [46] (1.8 mg GAE/g). Flavonoid levels (2.1 mg QE/g) were comparatively higher than some reports [46] and consistent with Oyesiku and Egunyomi [54]. The composition and concentration of phenolic compounds in SfIII were found to be influenced by environmental factors, including salinity, temperature, UV exposure, seasonality, and geographic

Table 3 Comparative assessment of antioxidant activities for both BSG and SfIII

ID	FRAP (μmol TE/g)	% Inhibition (DPPH)	IC ₅₀ (mg/g) ^a
BSG	30.0±0.04	34.0±2	17.4±2.5
SfIII	3.0±0.001	6.0±0.2	91.9±5.5

^aMilligrams of sample per gram required to achieve 50% inhibition (IC₅₀) in the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay. ± Standard deviation (3=replicates)

origin [97]. Moreover, extraction efficiency and the resulting profile of bioactive compounds were strongly affected by solvent polarity and extraction temperature, which govern the solubility and stability of phenolics [95].

Antioxidant Activity

The antioxidant activity of BSG and SfIII was evaluated through FRAP, DPPH % inhibition, and IC₅₀ assays (Table 3).

Logically, BSG displayed substantially higher antioxidant activity than SfIII across all assays. In the FRAP assay, BSG exhibited a reducing power of 30±0.04 μmol TE/g, approximately tenfold greater than SfIII (3±0.001 μmol TE/g). This elevated reducing capacity reflects the abundance of electron-donating compounds, primarily polyphenols and reducing sugars, which is consistent with our compositional analyses presented above [55].

The DPPH assay confirmed this trend, with BSG achieving 34±2% inhibition, consistent with moderate-to-high activity reported for barley and wheat byproducts (22–46% inhibition) [80, 98]. In contrast, SfIII demonstrated minimal radical scavenging (6±0.2% inhibition) and a high IC₅₀ (91.9±5.5 mg/g), aligning with previous reports on *S. fluitans* extracts [96]. The observed variability in *Sargassum* antioxidant activity, including reports of extracts reaching 63% inhibition, underscores the influence of seasonal metabolite fluctuations and extraction protocols on bioactivity [55, 96].

The DPPH assay confirmed this trend, with BSG achieving 34±2% inhibition, consistent with moderate-to-high activity reported for barley and wheat byproducts (22–46% inhibition) [82, 87]. In contrast, SfIII demonstrated minimal radical scavenging (6±0.2% inhibition) and a high IC₅₀ (91.9±5.5 mg/g), aligning with previous reports on *S. fluitans* extracts [85]. The observed variability in *Sargassum* antioxidant activity, including reports of extracts reaching 63% inhibition, underscores the influence of seasonal metabolite fluctuations and extraction protocols on bioactivity [45, 85].

FRAP and DPPH assays provide complementary information on the antioxidant response of complex biomass extracts, mainly through electron transfer-based mechanisms. Therefore, the antioxidant properties observed here

should be considered as indicators of potential activity, while additional assays based on complementary mechanisms would further contribute to a more complete characterization. Within this methodological framework, the higher antioxidant response observed for BSG highlights the presence of antioxidant compounds of interest that could be further investigated for functional applications, including natural preservative development [99, 100]. In contrast, although SfIII displayed limited radical scavenging activity, its high polysaccharide content and metal-binding properties indicate promising applications in heavy metal biosorption and the development of biodegradable UV-protective materials [6]. To fully exploit the antioxidant potential of these biomasses found in Benin, complementary assays such as ORAC and ABTS⁺ are recommended. Furthermore, optimizing extraction parameters could improve both the yield and bioactivity of key compounds, thereby expanding their potential for industrial applications.

Heavy Metal Analysis and Contamination Risk

Although these BGS and SfIII appear promising for establishing local value chains in Benin, it is essential to assess a final critical parameter, namely the potential presence of heavy metals, which could compromise certain high-value or sensitive applications. BSG samples exhibited low concentrations of toxic heavy metals, including cadmium (Cd < 0.01 mg/kg), lead (Pb ≤ 0.22 mg/kg), mercury (Hg: 0.02–0.14 mg/kg), and arsenic (As < 0.1 mg/kg). Essential trace metals, copper (Cu: 18–18.5 mg/kg) and zinc (Zn: 79.6–86 mg/kg), were within the typical range for cereal by-products [5]. Although the highest Pb level detected (0.22 mg/kg) approached the European Commission [101] Maximum Limits (MLs) for certain foodstuffs (0.1–0.2 mg/kg), the overall heavy metal content in BSG remained within safe margins for food and feed applications. The slight observed variation in Pb suggests that factors such as malt origin, water quality, or equipment maintenance may influence metal uptake.

In contrast, SfIII exhibited significantly higher levels of arsenic contamination, ranging from 29.5 to 41.1 mg/kg, consistent with reports on Caribbean *Sargassum* [57]. Cd (0.4–0.73 mg/kg) and Pb (0.96–1.35 mg/kg) frequently exceeded EU regulatory limits, whereas Cu, Zn, and Hg remained within acceptable levels. The elevated arsenic content, predominantly in toxic inorganic forms [102], renders the direct use of SfIII in food or feed unsafe without pretreatment strategies such as washing, blanching, or extraction. These findings highlight the necessity for rigorous monitoring to account for seasonal and inter-annual variability in contamination levels [57, 103].

Future Opportunities

Both BSG and SfIII exhibit compositional profiles that support a range of potential valorization pathways. Once dried, these materials may be integrated into biorefinery and material recovery schemes similar to those reported for other agro-industrial and macroalgal biomasses. However, these approaches should still be considered emerging opportunities rather than established industrial processes, as their implementation requires further techno-economic validation, process optimization, and site-specific feasibility assessments. A major consideration for both feedstocks is the observed interannual variability in composition, particularly in primary metabolites, which may limit their direct use in standardized applications requiring consistent feedstock quality. For SfIII, this variability is likely associated with natural fluctuations in environmental conditions, including seasonal changes, nutrient availability, and oceanographic processes influencing biomass growth and accumulation. Therefore, the use of SfIII for valorization should account for temporal variability and require systematic characterization of each harvested batch. In addition, SfIII also presents a constraint due to the presence of heavy metals such as arsenic, which limits its suitability for food-related applications without prior detoxification steps and comprehensive chemical characterization.

BSG has been widely investigated for food-related applications due to its protein and fibre content and favourable amino acid profile [5, 79]. Its incorporation into food products, particularly bakery and pasta formulations, has been shown to improve nutritional quality, with significant increases in dietary fibre and protein content while maintaining acceptable functional properties [104–106]. Beyond direct incorporation into foods, BSG has also been investigated within integrated biorefinery concepts that aim to fractionate proteins, phenolic compounds, and carbohydrate-rich residues into multiple value-added streams. Comparative studies illustrate that enzymatic hydrolysis preserves protein functionality, whereas subcritical water extraction favors phenolic recovery at the expense of protein techno-functional properties [107, 108]. These contrasting outcomes indicate that process selection should primarily depend on the targeted end-use application. In addition to protein recovery, the phenolic fraction represents another promising target for applications in cosmetics, nutraceuticals, and functional foods. A biorefinery approach combining selective phenolic extraction with controlled processing of the protein-enriched residue could generate multiple value-added streams, thereby linking waste valorization to potential nutritional and economic benefits, particularly in local contexts where such approaches could

contribute to improving resource efficiency and food ingredient availability.

In contrast, SfIII is less suitable for direct food applications due to compositional variability and heavy metal content, but it remains a promising feedstock for non-food valorization routes. Its lignocellulosic fraction supports potential conversion into platform chemicals such as furan derivatives, ethanol, or xylose [109]. Different pretreatment strategies have been explored, each presenting distinct advantages and limitations. Dilute-acid pretreatment favors fermentable sugar production but generates inhibitory compounds, whereas hydrothermal pretreatment reduces chemical consumption and facilitates hemicellulose recovery, although with lower furanic compound production [109, 110]. These contrasting outcomes highlight that the choice of pretreatment must be aligned with the targeted product portfolio and downstream processing requirements. For energy recovery, anaerobic digestion has been investigated as a valorization route, yet its overall performance remains highly dependent on digestate management and operational conditions, which may limit its economic viability in contexts lacking adequate infrastructure [57, 111]. Beyond biofuel production, SfIII has also been explored for technical material applications, including the fabrication of cellulose-based filtration membranes [112]. Finally, given its pronounced metal-chelating properties, SfIII represents a biomass resource of interest for exploring biosorption-based wastewater treatment systems. Leveraging this biomass in filtration or adsorption processes could substantially support national water purification efforts, contributing to improved water quality and potability.

Overall, the available literature indicates that the most appropriate valorization pathway depends on both the targeted end product and the compositional characteristics of the feedstock rather than on a universally optimal process. For BSG, food-oriented biorefinery strategies appear particularly promising due to the complementary recovery of proteins and phenolic compounds. Conversely, the compositional constraints of SfIII, notably its heavy metal content, make environmental and material applications more suitable than direct food uses. Future studies should therefore focus on validating these pathways by combining pilot-scale demonstrations with site-specific techno-economic and life cycle assessments under local conditions.

Conclusion and Perspectives

Brewers' Spent Grain (BSG) and *Sargassum fluitans* III (SfIII) from Benin represent underutilized biomasses with substantial potential to support sustainable local value chains. BSG is particularly notable for its high content of

polyphenols, condensed tannins, and electron-donating metabolites, which confer significant antioxidant and bioactive properties. These characteristics render BSG a compelling candidate for applications in nutraceuticals, functional foods, and natural preservative systems, offering avenues to integrate bioactive chemistry with industrial and health-oriented objectives. SfIII, while exhibiting comparatively lower radical scavenging capacity, is enriched in polysaccharides and metal-binding constituents, positioning it as a versatile feedstock for environmental and material science applications, including heavy metal biosorption and the development of biodegradable components. The detection of heavy metals and inorganic arsenic, however, underscores the necessity for rigorous pretreatment and quality monitoring to ensure safety in any food or feed-related uses.

Collectively, these findings highlight the capacity of BSG and SfIII to support local bioeconomy initiatives in Benin. Strategic valorization, through the optimization of extraction protocols, targeted functional applications, and integration into circular economy frameworks, could unlock substantial ecological, industrial, and socio-economic value, demonstrating the transformative potential of chemico-biological innovation in organic waste management in Benin. Future developments should also consider process requirements, including water consumption during biomass washing and other processing steps, to ensure that these valorization pathways remain environmentally sustainable and fully aligned with circular bioeconomy principles.

Acknowledgements J-C S. DOSSA extends his sincere gratitude to the Academy for Research and Higher Education of Belgium (ARES) for their financial support of this project. JCD is deeply thankful to Professor C. AKPOVI and Professor A. RICHEL for their invaluable guidance and mentorship throughout this study. Isabelle Van de Vreken is thanked for her fruitful technical assistance.

Funding DOSSA SETONDJI JEAN-CLAUDE reports that financial support was provided by the Academy of Research and Higher Education (ARES). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- da Almeida, A.R., Geraldo, M.R.F., Ribeiro, L.F., et al.: Compostos bioativos do bagaço de malte: compostos fenólicos, ácidos graxos e capacidade antioxidante in vitro. *Acta Sci. Technol.* **39**(3), 269–277 (2017). <https://doi.org/10.4025/actascitechnol.v39i3.28435>

2. Connolly, A., Piggott, C.O., FitzGerald, R.I.: Characterisation of protein-rich isolates and antioxidative phenolic extracts from pale and black brewers' spent grain. *Int. J. Food Sci. Technol.* **48**(8), 1670–1681 (2013). <https://doi.org/10.1111/ijfs.12137>
3. Qin, F., Johansen, A.Z., Mussatto, S.I.: Evaluation of different pretreatment strategies for protein extraction from brewer's spent grains. *Ind. Crops Prod.* **125**, 443–453 (2018). <https://doi.org/10.1016/j.indcrop.2018.09.017>
4. Mitri, S., Salameh, S.-J., Khelfa, A., et al.: Valorization of brewers' spent grains: pretreatments and fermentation, a review. *Fermentation*. **8**(10), 521 (2022). <https://doi.org/10.3390/fermentation8100521>
5. Mussatto, S.I., Dragone, G., Roberto, I.C.: Brewers' spent grain: generation, characteristics and potential applications. *J. Cereal Sci.* **43**(1), 1–14 (2006). <https://doi.org/10.1016/j.jcs.2005.06.001>
6. Davis, D., Simister, R., Campbell, S., et al.: Biomass composition of the golden tide pelagic seaweeds *Sargassum fluitans* and *S. natans* (morphotypes I and VIII) to inform valorization pathways. *Sci. Total. Environ.* **762**, 143134 (2021). <https://doi.org/10.1016/j.scitotenv.2020.143134>
7. Marx, U.C., Roles, J., Hankamer, B.: Sargassum blooms in the Atlantic Ocean—from a burden to an asset. *Algal Res.* **54**, 102188 (2021). <https://doi.org/10.1016/j.algal.2021.102188>
8. Lynch, M.K., Steffen, E.J., Arendt, E.K.: Brewers' spent grain: a review with an emphasis on food and health. *J. Inst. Brew.* **122**(4), 553–568 (2016). <https://doi.org/10.1002/jib.363>
9. Speede, R., Alleyne, K., Cox, S.-A.L.: Innovations for Sargassum Resilience. Centre for Resource Management and Environmental Studies (CERMES), Bridgetown. <http://www.cermes.uwi.edu/publications> (2024). Accessed 15 May 2026
10. Affan, H., Touati, K., Benzaama, M.H., et al.: Earth-based building incorporating *Sargassum muticum* seaweed: mechanical and hygrothermal performances. *Buildings* (2023). <https://doi.org/10.3390/buildings13040932>
11. Stanislas, T.T., Bilba, K., Potiron, C.O., Arsène, M.A.: Effect of desalination of Sargassum algae on its potential use as a stabilizer in sustainable earth-based bricks. *Algal Res.* **82**, 103625 (2024). <https://doi.org/10.1016/j.algal.2024.103625>
12. Institute for Environment and Sanitation Studies (IESS): Sargassum can reduce cost of building by 40 percent. University of Ghana, Accra. <https://iess.ug.edu.gh/news-events/sargassum-can-reduce-cost-building-40-percent> (2023). Accessed 10 June 2026
13. Eliopoulos, C., Arapoglou, D., Chorianopoulos, N., et al.: Conversion of brewers' spent grain into proteinaceous animal feed using solid state fermentation. *Environ. Sci. Pollut. Res.* **29**(20), 29562–29569 (2022). <https://doi.org/10.1007/s11356-021-15495-w>
14. BarthHaas: BarthHaas Report 2022/23—General. BarthHaas Group, Nuremberg. <https://www.barthhaas.com/resources/reports> (2023). Accessed 22 February 2026
15. Devnani, B., Moran, G.C., Grossmann, L.: Extraction, composition, functionality, and utilization of brewer's spent grain protein in food formulations. *Foods*. **12**(19), 3522 (2023). <https://doi.org/10.3390/foods12193522>
16. Jaeger, A., Zannini, E., Sahin, A.W., Arendt, E.K.: Barley protein properties, extraction and applications, with a focus on brewers' spent grain protein. *Foods* **10**(6), 1389 (2021). <https://doi.org/10.3390/foods10061389>
17. Macias-Garbutt, R., Serna-Hernández, S.O., Sosa-Hernández, J.E., Parra-Saldivar, R.: Phenolic compounds from brewer's spent grains: toward green recovery methods and applications in the cosmetic industry. *Front. Sustain. Food Syst.* **5**, 681646 (2021). <https://doi.org/10.3389/fsufs.2021.681646>
18. Chávez, V., Uribe-Martínez, A., Cuevas, E., et al.: Massive influx of pelagic *Sargassum* spp. on the coasts of the Mexican Caribbean 2014–2020: challenges and opportunities. *Water* **12**(10), 2908 (2020). <https://doi.org/10.3390/w12102908>
19. Resiere, D., Mehdaoui, H., Florentin, J., et al.: *Sargassum* seaweed health menace in the Caribbean: clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding. *Clin. Toxicol.* **59**(1), 1–9 (2020). <https://doi.org/10.1080/015563650.2020.1789162>
20. Smetacek, V., Zingone, A.: Green and golden seaweed tides on the rise. *Nature* **504**(7478), 84–88 (2013). <https://doi.org/10.1038/nature12860>
21. Wang, M., Hu, C., Barnes, B.B., et al.: The great Atlantic *Sargassum* belt. *Science* **364**(6435), 83–87 (2019). <https://doi.org/10.1126/science.aaw7912>
22. Alleyne, K.S.T., Neat, F., Oxenford, H.A.: A baseline assessment of the epiphytic community associated with pelagic sargassum in the Tropical Atlantic. *Aquat. Bot.* **186**, 103635 (2023). <https://doi.org/10.1016/j.aquabot.2023.103635>
23. Machado, C.B., Maddix, G.M., Francis, P., et al.: Pelagic Sargassum events in Jamaica: provenance, morphotype abundance, and influence of sample processing on biochemical composition of the biomass. *Sci. Total. Environ.* **817**, 152761 (2022). <https://doi.org/10.1016/j.scitotenv.2021.152761>
24. Adjahouinou, D.C., Hinlin, C., Kpogue Gangbazo, D.N.S., Sohoun, Z.: First assessment of the proximate, amino acid and mineral composition of sargassum from the Atlantic Ocean coast in the Benin Republic for fish feeding purposes. *J. Appl. Biosci.* **208**, 22070 (2025). <https://doi.org/10.35759/jabs.208.5>
25. Mussatto, S.I.: Brewer's spent grain: a valuable feedstock for industrial applications. *J. Sci. Food Agric.* **94**(7), 1264–1275 (2014). <https://doi.org/10.1002/jsfa.6486>
26. Masse, D., Ndiénor, M., Hien, E., et al.: Valorization agricole des déchets domestiques et industriels dans les agrosystèmes en Afrique de l'Ouest et à Madagascar. *Agron. Environ. Sociétés*. **8**(1), 45–56 (2018)
27. Kakai, H.F., Kakai, A.G., Tohouegnon, A.G.: Agriculture urbaine et valorization des déchets au Bénin: une approche de développement durable. *VertigO* (2011). <https://doi.org/10.4000/vertigo.9994>
28. Commission de la CEDEAO: Résidus agricoles et sous-produits agro-industriels en Afrique de l'ouest. CEDEAO, Abuja. <http://www.ecowas.int/publications> (2016). Accessed 14 March 2026
29. Ellen MacArthur Foundation: Circular economy in Africa: Food and agriculture opportunities. Ellen MacArthur Foundation, Cowes. <https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview> (2019). Accessed 18 April 2026
30. United Nations Environment Programme: Africa Waste Management Outlook. UNEP, Nairobi (2018)
31. Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F.: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. World Bank, Washington (2018). <https://doi.org/10.1596/978-1-4648-1329-0>
32. Schell, J.M., Goodwin, D.S., Siuda, A.N.S.: Recent sargassum inundation events in the Caribbean: shipboard observations reveal dominance of a previously rare form. *Oceanography* **28**(3), 8–10 (2015). <https://doi.org/10.5670/oceanog.2015.70>
33. Amaral-Zettler, L.A., Dragone, N.B., Schell, J., et al.: Comparative mitochondrial and chloroplast genomics of a genetically distinct form of *Sargassum* contributing to recent “Golden Tides” in the Western Atlantic. *Ecol. Evol.* **7**(2), 516–525 (2017). <https://doi.org/10.1002/ece3.2630>
34. Bousso, N.C., Brehmer, P., Ndiaye, W., et al.: Unusual holope-lagic *Sargassum* mass beaching in Northwest Africa: morphotypes, chemical composition, and potential valorisation. *Sci. Total. Environ.* **955**, 177018 (2024). <https://doi.org/10.1016/j.scitotenv.2024.177018>
35. Sluiter, A., Ruiz, R., Scarlata, C., et al.: Determination of Extrac-tives in Biomass; Laboratory Analytical Procedure (LAP). National Renewable Energy Laboratory (NREL), Golden, CO.

- Technical Report NREL/TP-510-42619, pp. 1–9 (2008). <https://www.nrel.gov/docs/gen/fy08/42619.pdf>. Accessed 12 April 2026
36. Blakeney, A.B., Harris, P.J., Henry, R.: A simple and rapid preparation of alditol acetates for monosaccharide analysis. *Carbohydr. Res.* **113**(2), 291–299 (1983). [https://doi.org/10.1016/0008-6215\(83\)88244-5](https://doi.org/10.1016/0008-6215(83)88244-5)
 37. Schmetz, Q., Teramura, H., Morita, K., et al.: Versatility of a dilute acid/butanol pretreatment investigated on various lignocellulosic biomasses to produce lignin, monosaccharides and cellulose in distinct phases. *ACS Sustain. Chem. Eng.* **7**(13), 11069–11079 (2019). <https://doi.org/10.1021/acssuschemeng.8b05841>
 38. Ortiz, J., Romero, N., Robert, P., et al.: Dietary fiber, amino acid, fatty acid and tocopherol contents of the edible seaweeds *Ulva lactuca* and *Durvillaea antarctica*. *Food Chem.* **99**(1), 98–104 (2006). <https://doi.org/10.1016/j.foodchem.2005.07.027>
 39. Siow, H.L., Gan, C.Y.: Extraction of antioxidative and antihypertensive bioactive peptides from *Parkia speciosa* seeds. *Food Chem.* **141**(4), 3435–3442 (2013). <https://doi.org/10.1016/j.foodchem.2013.06.030>
 40. Beccaria, M., Zou, Y., Stefanuto, P.H., et al.: Deeper investigation of oxygen-containing compounds in oleaginous feedstock (animal fat) by preparative column chromatography and comprehensive two-dimensional gas chromatography coupled with high-resolution time-of-flight mass spectrometry. *Talanta* **238**, 123019 (2022). <https://doi.org/10.1016/j.talanta.2021.123019>
 41. AOAC International: Lead, Cadmium, Copper, Iron, and Zinc in Foods. Official Method 999.11. In: Official Methods of Analysis of AOAC INTERNATIONAL, 22nd edn. Oxford University Press, New York (2023)
 42. Man, G., Xu, L., Wang, Y., et al.: Profiling phenolic composition in pomegranate peel from nine selected cultivars using UHPLC-QTOF-MS and UPLC-QQQ-MS. *Front. Nutr.* **8**, 807447 (2022). <https://doi.org/10.3389/fnut.2021.807447>
 43. Singleton, V.L., Orthofer, R., Lamuela-Raventós, R.M.: Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. *Methods Enzymol.* **299**, 152–178 (1999). [https://doi.org/10.1016/S0076-6879\(99\)99017-1](https://doi.org/10.1016/S0076-6879(99)99017-1)
 44. Kim, D.O., Jeong, S.W., Lee, C.Y.: Antioxidant capacity of phenolic phytochemicals from various cultivars of plums. *Food Chem.* **81**(3), 321–326 (2003). [https://doi.org/10.1016/S0308-8146\(02\)00423-5](https://doi.org/10.1016/S0308-8146(02)00423-5)
 45. Heimler, D., Vignolini, P., Dini, M.G., et al.: Antiradical activity and polyphenol composition of local Brassicaceae edible varieties. *Food Chem.* **99**(3), 464–469 (2006). <https://doi.org/10.1016/j.foodchem.2005.07.057>
 46. Ouattara, A., Yao, K., Komoe, K., et al.: Teneur en Composés Phénoliques et Activités Antioxydantes de *Sargassum fluitans* et *Sargassum natans*, deux Algues Brunes Invasives des Côtes Ivoiriennes. *Eur. Sci. J. ESJ* **18**(33), 313 (2022). <https://doi.org/10.19044/esj.2022.v18n33p313>
 47. Trigui, M., Hsouna, A.B., Tounsi, S., Jaoua, S.: Chemical composition and evaluation of antioxidant and antimicrobial activities of Tunisian *Thymelaea hirsuta* with special reference to its mode of action. *Ind. Crops Prod.* **41**, 150–157 (2013). <https://doi.org/10.1016/j.indcrop.2012.04.011>
 48. McCarthy, A.L., O'Callaghan, Y.C., Piggott, C.O., et al.: Brewers' spent grain; Bioactivity of phenolic component, its role in animal nutrition and potential for incorporation in functional foods: a review. *Proc. Nutr. Soc.* **72**(1), 117–125 (2013). <https://doi.org/10.1017/S002796631200082X>
 49. Alzate-Gaviria, L., Domínguez-Maldonado, J., Chablé-Villacís, R., et al.: Presence of polyphenols complex aromatic "lignin" in *Sargassum* spp. from Mexican Caribbean. *J. Mar. Sci. Eng.* **9**(1), 6 (2020). <https://doi.org/10.3390/jmse9010006>
 50. Cassoni, A.C., Costa, P., Mota, I., et al.: Recovery of lignins with antioxidant activity from brewer's spent grain and olive tree pruning using deep eutectic solvents. *Chem. Eng. Res. Des.* **192**, 34–43 (2023). <https://doi.org/10.1016/j.cherd.2023.01.053>
 51. de Crane d'Heysselaer, S., Bockstal, L., Jacquet, N., et al.: Potential for the valorisation of brewer's spent grains: a case study for the sequential extraction of saccharides and lignin. *Waste Manag. Res.* **40**(7), 1007–1014 (2022). <https://doi.org/10.1177/0734242X211055547>
 52. Ajanaku, K.O., Ademosun, T.O., Siyanbola, T.O., et al.: Improving nutritive value of maize-ogi as weaning food using wheat offal addition. *Curr. Res. Nutr. Food Sci. J.* **5**(3), 206–213 (2017). <https://doi.org/10.12944/CRNFSJ.5.3.04>
 53. Głowacki, S., Salamon, A., Sojak, M., et al.: The use of brewer's spent grain after beer production for energy purposes. *Materials* **15**(10), 3703 (2022). <https://doi.org/10.3390/ma15103703>
 54. O., O.O., A., E.: Identification and chemical studies of pelagic masses of *Sargassum natans* (Linnaeus) Gaillon and *S. fluitans* (Borgesen) Borgesen (brown algae), found offshore in Ondo State, Nigeria. *Afr. J. Biotechnol.* **13**(10), 1188–1193 (2014). <https://doi.org/10.5897/ajb2013.12335>
 55. Saldarriaga-Hernandez, S., Melchor-Martínez, E.M., Carrillo-Nieves, D., et al.: Seasonal characterization and quantification of biomolecules from sargassum collected from Mexican Caribbean coast—a preliminary study as a step forward to blue economy. *J. Environ. Manag.* **298**, 113507 (2021). <https://doi.org/10.1016/j.jenvman.2021.113507>
 56. Vázquez-Delfín, E., Freile-Pelegrín, Y., Salazar-Garibay, A., et al.: Species composition and chemical characterization of *Sargassum* influx at six different locations along the Mexican Caribbean coast. *Sci. Total. Environ.* **795**, 148852 (2021). <https://doi.org/10.1016/j.scitotenv.2021.148852>
 57. Milledge, J.M., Maneein, S., López, E.A., Bartlett, D.: *Sargassum* inundations in Turks and Caicos: methane potential and proximate, ultimate, lipid, amino acid, metal and metalloid analyses. *Energies* **13**(6), 1523 (2020). <https://doi.org/10.3390/en13061523>
 58. Khaled, A., Hessein, A., Abdel-Halim, A.M., Morsy, F.M.: Distribution of heavy metals in seaweeds collected along Marsa-Matrouh beaches, Egyptian Mediterranean sea. *Egypt. J. Aquat. Res.* **40**(4), 363–371 (2014). <https://doi.org/10.1016/j.ejar.2014.11.007>
 59. Melyon, S., Reig Rodrigo, P., Sénard, M., et al.: Investigating the inhibitory effect of *Sargassum natans* and *Sargassum fluitans* extracts on iron corrosion in 1.00 mol L⁻¹ HCl solution. *Coatings* **14**(10), 1316 (2024). <https://doi.org/10.3390/coatings14101316>
 60. Faulds, C.B., Robertson, J.A., Waldron, K.W.: Effect of pH on the solubilization of brewers' spent grain by microbial carbohydrases and proteases. *J. Agric. Food Chem.* **56**(16), 7038–7043 (2008). <https://doi.org/10.1021/jf800433c>
 61. Khidzir, K., Abdullah, N., Periathamby, A.: Brewery spent grain: chemical characteristics and utilization as an enzyme substrate. *Malays. J. Sci.* **29**(1), 41–51 (2010). <https://doi.org/10.22452/mjs.vol29no1.7>
 62. del Río, J.C., Prinsen, P., Gutiérrez, A.: Chemical composition of lipids in brewer's spent grain: a promising source of valuable phytochemicals. *J. Cereal Sci.* **58**(2), 248–254 (2013). <https://doi.org/10.1016/j.jcs.2013.07.001>
 63. Forssell, P., Kontkanen, H., Schols, H.A., et al.: Hydrolysis of brewers' spent grain by carbohydrate degrading enzymes. *J. Inst. Brew.* **114**(4), 306–314 (2008). <https://doi.org/10.1002/j.2050-0416.2008.tb00774.x>
 64. Robertson, J.A., l'Anson, K.J.A., Treimo, J., et al.: Profiling brewers' spent grain for composition and microbial ecology at the site of production. *LWT-Food Sci. Technol.* **43**(6), 890–896 (2010). <https://doi.org/10.1016/j.lwt.2010.01.019>
 65. Dewinta, A.F., Susetya, I.E., Suriani, M.: Nutritional profile of *Sargassum* sp. from Pane Island, Tapanuli Tengah as a component

- of functional food. J. Phys. Conf. Ser. **1542**, 012024 (2020). <https://doi.org/10.1088/1742-6596/1542/1/012024>
66. Tulashie, S.K., Akonnor Osei, C., Kwofie, R., et al.: The potential production of biofuel from *Sargassum* sp.: turning the waste catastrophe into an opportunity. Biofuels (2024). <https://doi.org/10.1080/17597269.2024.2306008>
 67. Hardouin, K., Bedoux, G., Burlot, A.S., et al.: Enzymatic recovery of metabolites from seaweeds: potential applications. Adv. Bot. Res. **71**, 279–320 (2014). <https://doi.org/10.1016/B978-0-12-408062-1.00010-X>
 68. Milledge, J.M., Harvey, P.J.: Golden Tides: problem or golden opportunity? The valorisation of *Sargassum* from beach inundations. J. Mar. Sci. Eng. **4**(1), 21 (2016). <https://doi.org/10.3390/jmse4010021>
 69. Fărcaș, A.C., Socaci, S.A., Dulf, F.V., et al.: Volatile profile, fatty acids composition and total phenolics content of brewers' spent grain by-product with potential use in the development of new functional foods. J. Cereal Sci. **64**, 34–42 (2015). <https://doi.org/10.1016/j.jcs.2015.04.003>
 70. Ganesan, A.R., Tiwari, U., Rajauria, G.: Seaweed nutraceuticals and their therapeutic role in disease prevention. Food Sci. Hum. Wellness. **8**(3), 252–263 (2019). <https://doi.org/10.1016/j.fshw.2019.03.001>
 71. van Ginneken, V.J., Helsper, J.P.F., de Visser, W., et al.: Polyunsaturated fatty acids in various macroalgal species from north Atlantic and tropical seas. Lipids Health Dis. **10**, 104 (2011). <https://doi.org/10.1186/1476-511X-10-104>
 72. Conde, E., Moure, A., Domínguez, H.: Supercritical CO₂ extraction of fatty acids, phenolics and fucoxanthin from freeze-dried *Sargassum muticum*. J. Appl. Phycol. **27**(2), 957–964 (2015). <https://doi.org/10.1007/s10811-014-0389-0>
 73. Khotimchenko, S.V.: Fatty acid composition of seven *Sargassum* species. Phytochemistry **30**(8), 2639–2641 (1991). [https://doi.org/10.1016/0031-9422\(91\)85114-6](https://doi.org/10.1016/0031-9422(91)85114-6)
 74. Schmid, M., Kraft, L.G.K., van der Loos, L.M., et al.: Southern Australian seaweeds: a promising resource for omega-3 fatty acids. Food Chem. **265**, 70–77 (2018). <https://doi.org/10.1016/j.foodchem.2018.05.060>
 75. Fleurence, J., Morancès, M., Dumay, J.: Seaweed proteins. In: Proteins in food processing, 2nd edn, pp. 245–262. Elsevier, Amsterdam (2017). <https://doi.org/10.1016/B978-0-08-100722-8.00010-3>
 76. El Din, N.G.S., El-Sherif, Z.M.: Nutritional value of some algae from the north-western Mediterranean coast of Egypt. J. Appl. Phycol. **24**(3), 613–626 (2012). <https://doi.org/10.1007/s10811-012-9831-3>
 77. Gressler, V., Fujii, M.T., Martins, A.P., et al.: Biochemical composition of two red seaweed species grown on the Brazilian coast. J. Sci. Food Agric. **91**(9), 1687–1692 (2011). <https://doi.org/10.1002/jsfa.4370>
 78. Angell, A.R., Mata, L., de Nys, R., Paul, N.A.: The protein content of seaweeds: a universal nitrogen-to-protein conversion factor of five. J. Appl. Phycol. **28**(1), 511–524 (2016). <https://doi.org/10.1007/s10811-015-0650-1>
 79. Ikram, S., Huang, L.Y., Zhang, H., et al.: Composition and nutrient value proposition of brewers spent grain. J. Food Sci. **82**(10), 2232–2242 (2017). <https://doi.org/10.1111/1750-3841.13794>
 80. Spinelli, S., Conte, A., Lecce, L., et al.: Supercritical carbon dioxide extraction of brewer's spent grain. J. Supercrit. Fluids **107**, 69–74 (2016). <https://doi.org/10.1016/j.supflu.2015.08.017>
 81. Bonifácio-Lopes, T., Vilas Boas, A.A., Coscueta, E.R., et al.: Bioactive extracts from brewer's spent grain. Food Funct. **11**(10), 8963–8977 (2020). <https://doi.org/10.1039/d0fo01426e>
 82. Coelho, E., Rocha, M.A.M., Moreira, A.S.P., et al.: Revisiting the structural features of arabinoxylans from brewers' spent grain. Carbohydr. Polym. **139**, 167–176 (2016). <https://doi.org/10.1016/j.carbpol.2015.12.006>
 83. Ismail, G.A.: Biochemical composition of some Egyptian seaweeds with potent nutritive and antioxidant properties. Food Sci. Technol. **37**(2), 294–302 (2017). <https://doi.org/10.1590/1678-457x.20316>
 84. Dawczynski, C., Schubert, R., Jahreis, G.: Amino acids, fatty acids, and dietary fibre in edible seaweed products. Food Chem. **103**(3), 891–899 (2007). <https://doi.org/10.1016/j.foodchem.2006.09.041>
 85. World Health Organization: Protein and amino acid requirements in human nutrition: report of a joint WHO/FAO/UNU expert consultation. WHO Technical Report Series, no. 935. World Health Organization, Geneva (2007)
 86. Fahy, E., Subramaniam, S., Brown, H.A., et al.: A comprehensive classification system for lipids. J. Lipid Res. **46**(5), 839–861 (2005). <https://doi.org/10.1194/jlr.E400004-JLR200>
 87. Schmitz, G., Ecker, J.: The opposing effects of n–3 and n–6 fatty acids. Prog. Lipid Res. **47**(2), 147–155 (2008). <https://doi.org/10.1016/j.plipres.2007.12.004>
 88. Van Meer, G., Voelker, D.R., Feigenson, G.W.: Membrane lipids: where they are and how they behave. Nat. Rev. Mol. Cell Biol. **9**(2), 112–124 (2008). <https://doi.org/10.1038/nrm2330>
 89. Moreau, R.A., Nyström, L., Whitaker, B.D., et al.: Phytosterols and their derivatives: structural diversity, distribution, metabolism, analysis, and health-promoting uses. Prog. Lipid Res. **70**, 35–61 (2018). <https://doi.org/10.1016/j.plipres.2018.04.001>
 90. You, X., Wakana, D., Ishikawa, K., et al.: Antifungal activity of compounds isolated from Bamboo Vermicompost against *Rhizoctonia solani* AG1-IB. Adv. Microbiol. **9**(12), 957–970 (2019). <https://doi.org/10.4236/aim.2019.912061>
 91. Dawood, K.M.: An update on benzofuran inhibitors: a patent review. Expert Opin. Ther. Pat. **29**(11), 841–870 (2019). <https://doi.org/10.1080/13543776.2019.1673587>
 92. Yadav, P., Singh, P., Tewari, A.K.: Design, synthesis, docking and anti-inflammatory evaluation of novel series of benzofuran based prodrugs. Bioorg. Med. Chem. Lett. **24**(10), 2251–2255 (2014). <https://doi.org/10.1016/j.bmcl.2014.03.087>
 93. Horn, P.A., Pedron, N.B., Junges, L.H., et al.: Antioxidant profile at the different stages of craft beers production: the role of phenolic compounds. Eur. Food Res. Technol. **247**(2), 439–452 (2021). <https://doi.org/10.1007/s00217-020-03637-2>
 94. Meneses, N.G.T., Martins, S., Teixeira, J.A., Mussatto, S.I.: Influence of extraction solvents on the recovery of antioxidant phenolic compounds from brewer's spent grains. Sep. Purif. Technol. **108**, 152–158 (2013). <https://doi.org/10.1016/j.seppur.2013.02.015>
 95. Muhamad, N., Muhmed, S., Yusoff, M., Gimbut, J.: Influence of solvent polarity and conditions on extraction of antioxidant, flavonoids and phenolic content from *Averrhoa bilimbi*. J. Food Sci. Eng. **4**(5), 255–260 (2014). <https://doi.org/10.17265/2159-5828/2014.05.006>
 96. Fagundo-Mollineda, A., Robledo, D., Vásquez-Elizondo, R.M., Freile-Pelegrin, Y.: Antioxidant activities in holopelagic *Sargassum* species from the Mexican Caribbean: temporal changes and intra-thallus variation. Algal Res. **76**, 103289 (2023). <https://doi.org/10.1016/j.algal.2023.103289>
 97. Kamal, M., Abdel-Raouf, N., Alwutayd, K., et al.: Seasonal changes in the biochemical composition of dominant macroalgal species along the Egyptian Red Sea shore. Biology (2023). <https://doi.org/10.3390/biology12030411>
 98. Iriti, M., Waisundara, V.Y., Palmioli, A., et al.: Valorization of heat-treated brewers' spent grain through the identification of bioactive phenolics by UPLC-PDA and evaluation of their antioxidant activities. Front. Nutr. **8**, 634519 (2021). <https://doi.org/10.3389/fnut.2021.634519>

99. Leichtweis, M.G., Oliveira, M.B.P.P., Ferreira, I.C.F.R., et al.: Sustainable recovery of preservative and bioactive compounds from food industry bioresidues. *Antioxidants* **10**(11), 1827 (2021). <https://doi.org/10.3390/antiox10111827>
100. Shahidi, F.: Antioxidants in food and food antioxidants. *Nahrung* **44**(3), 158–163 (2000). [https://doi.org/10.1002/1521-3803\(20000501\)44:3%3c158::AID-FOOD158%3e3.0.CO;2-L](https://doi.org/10.1002/1521-3803(20000501)44:3%3c158::AID-FOOD158%3e3.0.CO;2-L)
101. European Commission: Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *Off. J. Eur. Union*. L 119, 1–55 (2023). <https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=CELEX:32023R0915>. Accessed 18 March 2026
102. Rodríguez-Martínez, R.E., Roy, P.D., Torrescano-Valle, N., et al.: Element concentrations in pelagic *Sargassum* along the Mexican Caribbean coast in 2018–2019. *PeerJ* **8**, e8667 (2020). <https://doi.org/10.7717/peerj.8667>
103. Peng, Z., Guo, Z., Wang, Z., et al.: Species-specific bioaccumulation and health risk assessment of heavy metal in seaweeds in tropic coasts of South China Sea. *Sci. Total. Environ.* **832**, 155031 (2022). <https://doi.org/10.1016/j.scitotenv.2022.155031>
104. Sahin, A.W., Hardiman, K., Atzler, J.J., et al.: Rejuvenated Brewer's Spent Grain: the impact of two BSG-derived ingredients on techno-functional and nutritional characteristics of fibre-enriched pasta. *Innov. Food Sci. Emerg. Technol.* **68**, 102633 (2021). <https://doi.org/10.1016/j.ifset.2021.102633>
105. Cuomo, F., Trivisonno, M.C., Iacovino, S., et al.: Sustainable reuse of brewer's spent grain for the production of high protein and fibre pasta. *Foods* (2022). <https://doi.org/10.3390/foods11050642>
106. Nocente, F., Natale, C., Galassi, E., et al.: Using einkorn and tritordeum brewers' spent grain to increase the nutritional potential of durum wheat pasta. *Foods* (2021). <https://doi.org/10.3390/foods10030502>
107. Yu, D., Sun, Y., Wang, W., et al.: Recovery of protein hydrolysates from brewer's spent grain using enzyme and ultrasonication. *Int. J. Food Sci. Technol.* **55**(1), 357–368 (2020). <https://doi.org/10.1111/ijfs.14314>
108. Alonso-Riaño, P., Sanz, M.T., Benito-Román, O., et al.: Subcritical water as hydrolytic medium to recover and fractionate the protein fraction and phenolic compounds from craft brewer's spent grain. *Food Chem.* **351**, 129264 (2021). <https://doi.org/10.1016/j.foodchem.2021.129264>
109. Borines, M.G., de Leon, R.L., Cuello, J.L.: Bioethanol production from the macroalgae *Sargassum* spp. *Bioresour. Technol.* **138**, 22–29 (2013). <https://doi.org/10.1016/j.biortech.2013.03.108>
110. del Río, P.G., Gullón, B., Pérez-Pérez, A., et al.: Microwave hydrothermal processing of the invasive macroalgae *Sargassum muticum* within a green biorefinery scheme. *Bioresour. Technol.* **340**, 125733 (2021). <https://doi.org/10.1016/j.biortech.2021.125733>
111. Milledge, J.M., Harvey, P.J.: The utilisation of *Sargassum* for the production of biofuels and value-added products: a review. *Bioresour. Technol.* **298**, 122569 (2020). <https://doi.org/10.1016/j.biortech.2019.122569>
112. Quellmalz, A., Mihranyan, A.: Citric acid cross-linked nanocellulose-based paper for size-exclusion nanofiltration. *ACS Biomater. Sci. Eng.* **1**(5), 271–276 (2015). <https://doi.org/10.1021/ab500161x>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.