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AS MACROALGAS MARINHAS: POTENCIAL NUTRICIONAL, TECNO-FUNCIONAL E APLICAÇÃO EM PRODUTOS EXTRUSADOS

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Tese apresentada à Faculdade de Engenharia de Alimentos da Universidade Estadual de Campinas como pré-requisito para obtenção do título de Doutora em Tecnologia de Alimentos.

Orientadora: Profª. Drª. Maria Teresa Pedrosa Silva Clerici

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RESUMO

Modificações na cadeia alimentar são essenciais para alcançar os Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas, que visam promover dietas saudáveis e reduzir o impacto ambiental. As algas marinhas emergem como uma matéria-prima promissora devido ao seu alto valor nutritivo e à diversidade de biocompostos, incluindo polissacarídeos, proteínas, fibras alimentares, ácidos graxos ômega-3, compostos fenólicos, carotenoides, vitaminas e minerais. Dentro deste contexto, e considerando o potencial do Brasil, este estudo caracteriza a alga marinha parda *Sargassum* sp., coletada no litoral de São Paulo, Brasil, em termos de suas propriedades nutricionais e tecno-funcionais, e avalia o potencial de aplicação dessa alga em produtos extrusados, com o objetivo de fomentar o desenvolvimento futuro de produtos alimentícios inovadores. Para alcançar esses objetivos, o trabalho foi dividido em três fases. Inicialmente, foram realizadas revisões abrangentes da literatura sobre algas marinhas, seu potencial nutricional e suas aplicações na indústria de alimentos, bem como seu uso como fonte de amido não convencional. Essas revisões impulsionaram as fases seguintes, nas quais foram caracterizadas as propriedades nutricionais e tecno-funcionais da alga marinha *Sargassum filipendula* utilizando dois métodos de secagem: secagem em estufa (SD) e liofilização (SL). Uma amostra comercial do gênero *Sargassum* (SC) foi adquirida seca no mercado chinês e utilizada como controle. Esse estudo demonstrou que as farinhas de algas marinhas (SD, SL e SC) apresentaram diferenças significativas na composição físico-química, com teor de fibra alimentar superior a 70%. Os ácidos glutâmico e aspártico foram os aminoácidos mais abundantes. Em relação aos compostos bioativos, as farinhas SL apresentaram os maiores teores. A amostra SL apresentou coloração mais clara em comparação com SD e SC. A formação de emulsão, a capacidade de formação de espuma e a estabilidade foram maiores no SL, assim como a absorção de água e óleo. Na última etapa, quatro formulações foram submetidas a extrusão termoplástica: uma somente com farinha de arroz (R), uma com farinha de arroz e 1,5% de algas secas em estufa (R+SD), outra com farinha de arroz e 1,5% de algas secas por liofilização (R+SL), e outra com farinha de arroz e 1,5% de algas comerciais (R+SC). Os resultados indicam o potencial das algas marinhas como ingredientes funcionais em produtos extrusados, contribuindo para o desenvolvimento de alimentos com benefícios à saúde. A escolha do método de secagem das algas é fundamental para otimizar as propriedades tecno-funcionais dos produtos finais. Em conclusão, esta tese reforça o potencial das algas marinhas como ingredientes funcionais, contribuindo para o desenvolvimento de alimentos mais saudáveis e nutritivos. A pesquisa abre caminho para futuras investigações sobre o uso de algas marinhas em diversas matrizes alimentares e tecnologias de processamento, visando sempre a inovação e os benefícios à saúde.

Palavras-chave: Algas marinhas; *Sargassum filipendula*; Propriedades nutricionais; Secagem em estufa; Liofilização; Produtos extrusados; Ingredientes funcionais.

ABSTRACT

Modifications in the food chain are essential to achieve the United Nations' Sustainable Development Goals (SDGs), which aim to promote healthy diets and reduce environmental impact. Seaweeds emerge as a promising raw material due to their high nutritional value and diversity of biocompounds, including polysaccharides, proteins, dietary fibers, omega-3 fatty acids, phenolic compounds, carotenoids, vitamins, and minerals. In this context, and considering Brazil's potential, this study characterizes the brown seaweed Sargassum sp., collected on the coast of São Paulo, Brazil, in terms of its nutritional and techno-functional properties, and evaluates the potential application of this seaweed in extruded products, with the aim of fostering the future development of innovative food products. To achieve these objectives, the work was divided into three phases. Initially, comprehensive literature reviews were conducted on seaweeds, their nutritional potential, their applications in the food industry, and their use as a source of non-conventional starch. These reviews propelled the subsequent phases, in which the nutritional and techno-functional properties of the seaweed *Sargassum filipendula* were characterized using two drying methods: oven drying (SD) and freeze drying (SL). A commercial sample of the *Sargassum* genus (SC) was purchased dried from the Chinese market and used as a control. This study demonstrated that the seaweed flours (SD, SL, and SC) exhibited significant differences in physicochemical composition, with dietary fiber content exceeding 70%. Glutamic and aspartic acids were the most abundant amino acids. Regarding bioactive compounds, the SL flours had the highest levels. The SL sample had a lighter color compared to SD and SC. Emulsion formation, foam formation capacity, and stability were higher in SL, as well as water and oil absorption. In the final stage, four formulations were subjected to thermoplastic extrusion: one with only rice flour (R), one with rice flour and 1.5% oven-dried seaweed (R+SD), another with rice flour and 1.5% freeze-dried seaweed (R+SL), and another with rice flour and 1.5% commercial seaweed (R+SC). The results indicate the potential of seaweeds as functional ingredients in extruded products, contributing to the development of foods with health benefits. The choice of seaweed drying method is crucial to optimize the techno-functional properties of the final products. In conclusion, this thesis reinforces the potential of seaweeds as functional ingredients, contributing to the development of healthier and more nutritious foods. The research paves the way for future investigations into the use of seaweeds in various food matrices and processing technologies, always aiming for innovation and health benefits.

Keywords: Seaweeds; *Sargassum filipendula*; Nutritional properties; Oven drying; Freeze drying; Extruded products; Functional ingredients.

SUMÁRIO

1 INTRODUÇÃO

Modificações na cadeia alimentar são essenciais para atingir os Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas relacionados à promoção de dietas saudáveis e à redução do impacto ambiental (ONU, 2015). Estima-se que a população mundial passará de 8 bilhões de pessoas hoje para aproximadamente 10 bilhões de pessoas em 2050, o que se traduz em um aumento da necessidade de produção de alimentos, sendo improvável que esse aumento de produção continue seja alcançado usando apenas os recursos disponíveis atualmente na terra (MALAFRONTE *et al*., 2021). Entre os recursos alimentares disponíveis nos oceanos, as algas marinhas foram identificadas como um dos futuros alimentos que contribuirão para transformar nosso sistema alimentar global, fato que já foi previsto por Josué de Castro no livro Geografia da Fome (CASTRO, 1961).

As algas marinhas são consideradas uma fonte de alimento pró-ambiental, uma vez que não precisam de terras aráveis para crescer, seu cultivo não requer fertilizantes, pesticidas ou água doce, alimentam-se através da fotossíntese e também são um sumidouro natural de carbono (GOVAERTS; OLSEN, 2022). Além disso, têm sido apontadas como uma matéria-prima promissora, pois são altamente nutritivas e possuem uma grande variedade de biocompostos, como polissacarídeos, proteínas, ácidos graxos ômega-3, carotenoides, compostos fenólicos, vitaminas e minerais (ROOHINEJAD *et al*., 2017; GULLÓN *et al*., 2020).

Numerosos estudos foram realizados sobre a incorporação de algas marrons e seus extratos em várias matrizes alimentares com o objetivo de melhorar as características nutricionais (KIM *et al*., 2010) e tecnológicas (NUÑEZ; PICON, 2017; OH *et al*., 2020) como textura (ARUFE *et al*., 2018) e capacidade antioxidante em produtos alimentícios (ROZYLO *et al*., 2017). Para além das propriedades tecnológicas e nutricionais das algas marinhas, estudos têm demonstrado os seus benefícios para a saúde, como a redução de doenças como a obesidade (MAEDA *et al*., 2005), dislipidemia (PANLASIGUI *et al.*, 2003), hipertensão (WADA *et al*., 2021), diabetes (LEE *et al*., 2010) e alguns tipos de câncer (NELSON *et al*., 2017), bem como anti-inflamatórios (BERGÉ *et al*., 2002) e imunomoduladores (MIYAKE *et al*., 2002).

Outro ponto importante a destacar é que a demanda do consumidor por alimentos à base de plantas está aumentando (MILINOVIC *et al*., 2021), juntamente com a conscientização sobre questões relacionadas aos benefícios à saúde e sustentabilidade ambiental das escolhas de alimentos (RAJA *et al*., 2022). Novos produtos alimentícios com adição de algas marinhas

estão sendo desenvolvidos em ritmo crescente (AL-THAWADI, 2018), assim como o consumo de algas marinhas cruas, secas ou como ingrediente em outros produtos alimentícios (GOVAERTS; OLSEN, 2022).

Em produtos de panificação, as algas marinhas podem ser incorporadas para melhorar sua qualidade nutricional, fornecendo nutrientes como proteínas, fibras alimentares e compostos bioativos (PRABHASANKAR *et al.,* 2009), visto que, em sua maioria, esta classe de produtos tem como ingrediente principal a farinha de trigo e sua contribuição nutricional na dieta é o fornecimento de carboidratos (QUITRAL *et al.,* 2022). Além disso, as algas marinhas podem promover algumas modificações em determinados parâmetros tecnológicos, como aumentar a capacidade de retenção de água (PRABHASANKAR *et al.,* 2009) e formar misturas mais estáveis (KIM *et al.,* 2010).

A procura por alimentos prontos para consumo e saudáveis tem aumentado. Processos que podem ser versáteis e contribuir para inclusão de novos ingredientes têm sido explorados, dentre as tecnologias de fabricação utilizadas atualmente se destaca a extrusão. A extrusão termoplástica é um processo que utiliza altas temperaturas (120 a 160 °C) durante um curto período de tempo (15 a 30s), de forma contínua e homogênea (WOLF, 2010). O trabalho mecânico, o calor e as forças de cisalhamento aplicadas resultam em mudanças em sua forma, estrutura e composição. Com isso, é possível desenvolver alimentos de consumo prático, com uma variedade de formas, texturas e sabores (LAZOU; KROKIDA, 2010).

Dentre as matérias-primas que podem ser associadas a algas marinhas destaca-se a farinha de arroz, cujo uso nos países asiáticos já está bem estabelecido, tem se repetido no Brasil, pois apresenta boa combinação sensorial e nutricional quando associado a algas marinhas. A farinha de arroz pode ser usada como ingrediente chave na produção de diferentes alimentos à base de arroz, como macarrão, pães, bolos entre outros (QIAN; ZHANG, 2013). Dentro do conceito de sustentabilidade, a farinha de arroz produzida no Brasil é proveniente do arroz quebrado, co-produto do beneficiamento do arroz branco polido, com menor valor comercial, e que pode ter a valorização da produção local e ampliação de sua utilização.

Embora haja avanços e pesquisas recentes, estimuladas pelo crescente interesse nas algas marinhas devido ao seu potencial como fonte de ingredientes funcionais e tecnológicos, a aplicação de algas no desenvolvimento de novos produtos, não só com melhores propriedades nutricionais e tecnológicas, mas também com propriedades funcionais ainda são subexploradas. Do ponto de vista econômico, as algas poderão ser promotoras de tendências para inserção social e desenvolvimento de novas cadeias alimentares, promovendo o desenvolvimento de

produtores, mercados locais costeiros e proteger o ambiente com preservação da vida marinha no entorno da costa, uma vez que ela passará a ser fonte importante de alimento benéfico à saúde. Além disso, as algas marinhas na alimentação podem atender a demanda do público vegano, sem glúten e dos consumidores que buscam por alimentos funcionais mais saudáveis e sustentáveis.

É preciso destacar o potencial do Brasil no cultivo de algas, principalmente porque o país possui 8.698 km de litoral (IBGE, 2019) e condições marítimas favoráveis ao cultivo de algas. Além disso, 18% da população brasileira ou cerca de 37 milhões de habitantes divididos em 279 municípios vivem na faixa litorânea do Brasil (IBGE, 2022).

Como exemplo de sucesso nacional, o Estado de Santa Catarina já implantou centenas de fazendas de algas marinhas e inaugurou em 2023 a primeira unidade de processamento de macroalgas, que produzirá e comercializará algas desidratadas para consumo humano, o que mostra o grande potencial para toda a costa brasileira, incluindo o litoral do Estado de São Paulo, cujo estudo da alga *Sargassum* sp foi iniciado pelo nosso grupo de pesquisa (Figura 1).

Figura 1. Imagens do banco de algas Sargassum sp. localizado na Praia das Cigarras, São Sebastião - SP, Brasil, em seu habitat rochoso antes da coleta (A); e após a coleta (B), realizada pela própria pesquisadora em fevereiro de 2022.

Neste contexto, o objetivo deste estudo foi caracterizar a alga marinha parda *Sargassum* sp. coletada no litoral de São Paulo, Brasil, quanto às suas propriedades nutricionais e tecno-funcionais utilizando dois métodos de secagem e avaliar o potencial de aplicação desta alga em produtos extrusados, visando o futuro desenvolvimento de produtos inovadores.

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Brown algae and their multiple applications as functional ingredient in food production

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Review

Brown algae and their multiple applications as functional ingredient in food production

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ABSTRACT

Brown algae are considered one of the resources that can contribute to transforming our global food system by promoting healthier diets and reducing environmental impact. In this sense, this review article aims to provide up-to-date information on the nutritional and functional improvement of brown algae when they are applied to different food matrices. Brown algae present sulfated polysaccharides (alginates, fucoidans, and laminarins), proteins, minerals, vitamins, dietary fibers, fatty acids, pigments, and bioactive compounds that can positively contribute to the development of highly nutritious food products, as well as used reformulate products already existing, to remove, reduce, increase, add and/or replace different components and obtain products that confer health-promoting properties. This review demonstrates that there is a tendency to use seaweed for the production of functional foods and that the number of commercially produced products from seaweed is increasing, that is, seaweed is a sector whose global market is expanding.

1. Introduction

Modifications in the food chain are essential for achieving the United Nations Sustainable Development Goals related to promoting healthy diets and reducing environmental impact (UNAtlas, 2015). The world population is estimated to increase from the current 8 billion people to approximately 10 billion people in 2050, which translates into an increase in the need for food production, and it is unlikely that this increase in production will be achieved using only land resources (Malafronte et al., 2021). Among the food resources available in the oceans, seaweed has been identified as one of the 50 future foods that will contribute to transforming our global food system.

Seaweeds are abundant in the ocean and for coastal communities, the extension of economic activities to the seas and oceans offers an excellent opportunity for growth and development (Prabhu, Israel, Palantnik, Silberman, & Golberg, 2020). The sustainable use and management of marine areas can provide new tools to fight poverty and enhance the consumption of other local food sources, such as algae and other sea species, beyond fish and seafood, in addition to being a strategy to protect coastal ecosystems.

Seaweed or algae is used as a synonym, representing the group of macroalgae found in seas and oceans. In this review article, we chose to use only seaweed to avoid confusion. Within the algae category, we will highlight the brown algae (Phaeophyceae or Phaeophyta) and their derivatives products, because they are already used in food products (Roohinejad et al., 2017; Afonso, Catarino, Silva, & Cardoso, 2019) and according to an overview of Buschmann et al. (2017) can be used in fertilizers, animal feed, biofuels, nutraceuticals, and pharmaceuticals.

Our review focuses on foods because, in the food industry, brown algae were predominantly used for technological functions, such as stabilization and thickening applications (Kadam, Álvarez, Tiwari, & O'Donnell, 2017), but nowadays, they are becoming sources of nutrients and bioactive substances (Shannon & Abu-Ghannam, 2019), especially their polysaccharides, which are indigestible for humans and play a role as dietary fiber, induce satiety, improve intestinal function, and have beneficial effects on the microbiota (Cassani et al., 2020); anti-inflammatory (Bergé, Debiton, Dumay, Durand, & Barthomeuf, 2002); dyslipidemia control (Panlasigui, Baello, Dimatangal, & Dumelod, 2003); reduced obesity (Maeda et al., 2005), diabetes control (Lee, Kim, Vitek, & Nam, 2010); immunomodulatory (Miyake et al., 2006) dyslipidemia (Panlasigui et al., 2003), hypertension control (Wada et al., 2021), diabetes (Lee et al., 2010), and some types of cancer (Nelson et al., 2017). Many studies incorporating brown algae and/or their extracts into various food matrices have been carried out to improve the

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nutritional (Kim et al., 2010) and technological characteristics (Nuñez & Picon, 2017; Oh, Lee, Kim, & Kim, 2020), as texture (Arufe et al., 2018) and antioxidant capacity of the products (Różyło, Hameed Hassoon, Gawlik-Dziki, Siastała, and Dziki, 2017).

Some reviews available describe the nutritional, pharmaceutical, and health aspects of brown algae (Gupta & Abu-Ghannam, 2011; Brown et al., 2014; Fernando, Kim, Kim, & Jeon, 2019; Polat et al., 2021; Ju et al., 2023; Park et al., 2023), and our article aims to provide up-to-date information on the nutritional and functional improvement of brown algae when they are applied in different food matrices.

2. Bibliographic research

A bibliographic search was carried out in five databases: Web of Science, ScienceDirect, Scopus, Scielo, and Google Scholar. Studies published up to 2022 were selected using the following search terms: "seaweed AND brown algae", "brown algae AND food", "brown algae AND meats", "brown algae AND meat products", "brown algae AND dairy products", "brown algae AND bakery products", "brown algae AND juice products", in the title, abstract and keywords. Only articles written in English about brown algae published in scientific journals were included. Another step involving data selection was the inclusion of official reports from international agencies (ie Food and Agriculture Organization of the United Nations – FAO).

3. Nutritional and functional properties of brown algae

Differences in the nutritional composition (Table 1) of brown algae are related to species, cultivation place, atmospheric conditions, harvest period, and seasonal variations (Peñalver et al., 2020). It can be seen in Table 1 that the vast majority of commercial brown algae were in the dehydrated form to increase their shelf life. The dehydration process promotes the enzymatic system inactivation, microbial growth inhibition, the desirable qualities of manutention and storage volume reduction (Gupta & Abu-Ghannam, 2011), which becomes more sustainable since it can be kept at room temperature and takes up less space during their commercialization.

Algae dehydration processes can be carried out in the sun, spreading them over a net or in greenhouses until the humidity is lower than 10% (Wong & Cheung, 2001; Dawczynski, Schubert, & Jahreis, 2007; Choi et al., 2015; Caballero, Flores, & Olivares, 2021). Before the algae dehydration, Rodriguez-Jasso, Mussatto, Pastrana, Aguilar, and Teixeira (2011), Biancarosa et al. (2018), and Oh et al. (2020) made the process of cleaning and sanitizing and they observed that if the processes were carried out, they should be mentioned, as they can significantly interfere with their nutrient content, due to loss the water-soluble compounds and changes in the composition of phytochemicals.

3.1. Polysaccharides

Algae are distinguished by the composition of the structural cell wall and reserve polysaccharides, which can vary from 2.6% (Wong & Cheung, 2001) to 66% (Jang, Cho, Jeong, & Kim, 2012) on a dry basis, depending on the species (Table 1). Brown algae had a higher content of sulfated polysaccharides than green and red algae, which can be composed of three different groups: alginates, fucoidans, and laminarins. Currently, these compounds are considered dietary fibers with a potential prebiotic effect (Seong et al., 2019; Oliveira, Carvalho, Nascimento, & Hertwig, 2019).

These non starchy polysaccharides, which do not add energetic value to the food, have been used as a filling agent when high amounts of sugars and fats are replaced in products, and it is necessary to maintain

Table 1
Proximate composition of different brown algae (g/100 g).

Seaweed	Sample	Carbohydrates	Dietary fiber			Protein	Fat	Ash	Reference
			TDF	IDF	SDF				
Sargassum hemiphyllum	dry	17.9	50.4	nd	nd	5.3	3.0	23.3	Wong and Cheung (2001)
Sargassum henslowianum		1.7	61.1	nd	nd	11.3	4.6	21.3	
Sargassum patens		2.6	54.8	nd	nd	7.5	6.1	28.8	
Himanthalia elongata	dry	nd	nd	nd	nd	5.4	0.9	26.7	Sánchez-Machado, López-Cervantes, López-Hernández, and Paseiro-Losada (2004)
Laminaria ochroleuca		nd	nd	nd	nd	7.5	0.9	29.5	
Undaria pinnatifida		nd	nd	nd	nd	18.0	1.0	31.2	
Undaria pinnatifida	dry	nd	45.9	nd	nd	19.8	4.5	nd	Dawczynski et al. (2007)
Laminaria sp.		nd	36.0	nd	nd	7.5	1.0	nd	
Hizikia fusiforme		nd	62.3	nd	nd	11.6	1.4	nd	
Himanthalia elongata	dry	nd	50.3	25.9	24.4	4.8	1.3	30.1	Cofrades et al. (2008)
Undaria pinnatifida		nd	40.9	28.4	12.5	11.9	0.8	36.8	
Undaria pinnatifida	dry	43.0	0.7	nd	nd	20.5	3.7	26.1	Prabhasankar et al. (2009)
Laminaria japonica	dry	66.0	nd	nd	nd	10.6	1.6	21.8	Jang et al. (2012)
Sargassum fulvellum		44.5	nd	nd	nd	19.9	0.5	35.1	
Undaria pinnatifida		52.0	nd	nd	nd	18.3	1.8	28.0	
Hizikia fusiforme		59.0	nd	nd	nd	13.9	0.4	26.6	
Laminaria japonica	dry	nd	51.2	nd	nd	7.8	1.2	27.3	Choi et al. (2012)
Undaria pinnatifida	dry	nd	nd	nd	nd	7.6	6.6	13.3	Choi et al. (2015)
Sargassum fusiforme		nd	nd	nd	nd	10.4	1.4	17.9	
Laminaria japonica		nd	nd	nd	nd	4.2	1.4	22.3	
Ascophyllum nodosum	dry	nd	nd	nd	nd	8.7	3.6	30.8	Lorenzo et al. (2017)
Fucus vesiculosus		nd	nd	nd	nd	12.9	3.7	20.7	
Bifurcaria bifurcate		nd	nd	nd	nd	8.9	6.5	31.7	
Ascophyllum nodosum	dry	56.7	nd	nd	nd	6.6	3.1	22.0	Różyło et al. (2017)
Ascophyllum nodosum	dry	nd	nd	nd	nd	5 to 10	nd	17 to 20	Pereira, Morrison, Shukla, and Critchley (2020)
Laminaria digitata	dry	55.80	nd	nd	nd	9.12	0.68	25.40	Malafronte et al. (2021)
Durvillaea antarctica	dry	54.6	nd	nd	nd	10.8	0.4	26.0	Caballero et al. (2021)
Macrocystis pyrifera		52.7	nd	nd	nd	9.8	0.2	30.5	
Lessonia nigrescens		48.4	nd	nd	nd	9.8	0.3	33.0	
Sargassum sp.	humid	nd	nd	nd	nd	3.0	0.6	7.1	Winarni et al. (2021)

Where: nd: not determined; TDF: Total Dietary Fibre; IDF: Insoluble Dietary Fibre; SDF: Soluble Dietary Fibre.

the mass amount of the portion to be consumed. Many examples are presented in Table 3, where can be seen that these polysaccharides can retain water in meat products (Choi et al., 2012), improve emulsion stability in creams, form a network in gluten-free products (Różyło et al., 2017; Fradinho, Raymundo, Sousa, Dominguez, & Torres, 2019), and very effectively increase viscosity in soups, broths, and beverages, it may be an option to add to products that you want to avoid phase separation, for example, vegetable beverages supplemented with soy proteins, where protein enrichment has been used.

3.1.1. Alginate

Alginates are composed of 20–30 units of alternative binding sequences of β-D manuronic (M) and α-L-guluronic acid (G), joined via 1,4-glycosidic linking (Praveen, Parvathy, Balasubramanian, & Jayabalan, 2019). The interaction of G-blocks in the presence of ions (Ca^{2+}) gives rigidity to the general structure, giving gel-forming properties to these polysaccharides. The brown algae cell walls have alginate in their constitution.

The yield and chemical structure of the extracted polysaccharides from brown algae can be affected by factors such as pH, temperature, time, pressure, and sample-to-solvent ratio used during extraction (Garcia-Vaquero, Rajauria, O'Doherty, & Sweeney, 2017), but alginate from algae is usually extracted by conventional methods of water-based (aqueous) extraction, diluted acidic extraction, and other chemical-based extraction (Rioux, Turgeon, & Beaulieu, 2007; Okolie, Subin, Udenigwe, Aryee, & Mason, 2017).

Regarding yield, Bertagnolli, Espindola, Kleinübing, Tasic, and Da Silva (2014) extracted alginate with acidic solvents from Brazilian algae collected on the coast of São Paulo State in different seasons of the year and obtained yields in the range of 15.1–17.2%. Fertah, Belfkira, and Dahmane (2017) found yields of 38.3–51.8% in the alga *Laminaria digitata* extracted with 0.2 M HCl under different conditions of time and temperature and concluded that the yield was affected by the extraction temperature and sample size. For both studies, the extraction yields were calculated by the ratio of dry initial seaweed mass and obtained dry alginate mass.

The emerging technologies (ultrasound and microwave) and enzymatic methods have been explored to increase yield, bioactivity, and industrial relevance (Praveen et al., 2019) when compared to traditional extraction, with water or solvents. Extraction with water alone is cheaper and ecologically correct, however, the yield is very low. Shi, Yan, Cheong, and Liu (2018) using ultrasound-aided extraction (UAE) reported the advantage of time efficiency, lower use of solvents, improved yield as well a huge possibility of industrial scale-up and automated process.

The most important characteristics of brown algae isolated alginates for foods are their ability to retain water, as well as their gelling, thickening, emulsifying, and stabilizing properties, (Kraan, 2012). In addition to its broad technological applications, alginate is associated with gastrointestinal health benefits, and its potential mechanisms of action in weight management have been investigated. Paxman, Richardson, Dettmar, and Corfe (2008) showed that, compared to a control (no alginate), consumption of a beverage containing 1.5 g of sodium alginate reduces the postprandial glucose spike, causing a slower rate of gastric emptying, which makes alginate a component of interest in brown algae.

3.1.2. Fucoidans

Fucoidans are constituted of branched chains of α-(1 → 2) bond-linked L-fucose 4 sulfate with the C3 ester group and a trace quantity of xylose, galactose, mannose, and uronans (Praveen et al., 2019), and like alginate, they have a structural role in brown algae, mainly in preventing dehydration (Cardoso, Pereira, Seca, Pinto, & Silva, 2015), because they are in the fibrillar cell walls and intercellular spaces of brown algae.

Some results of preclinical studies have shown that fucoidans have biological activities that include antioxidant, antitumor, immunoregulatory, anticoagulant, antithrombotic, antiviral, and anti-inflammatory effects, as demonstrated in the review by Wang et al. (2009). Huang, Wen, Gao, and Liu (2010) reported that ingestion of fucoidans from *Laminaria japonica* algae reduced serum levels of total cholesterol, triglycerides, and low-density lipoprotein cholesterol in hyperlipidemic rats. Shan et al. (2016) showed the α-glucosidase inhibitory effects of 11 fucoidans isolated from different brown algae. In this study, mice received fucoidans diluted in water by gavage and the authors concluded that fucoidans lowered fasting blood glucose and hemoglobin A1c levels, which may be a promising α-glucosidase inhibitor for the treatment of type 2 diabetes mellitus.

Reyes et al. (2020) discussed the use of fucoidans in clinical trials to assess their potential synergy with other anticancer therapies and concluded that fucoidans have molecular characteristics (molecular weight and sulphation grade) that enable chemical or enzymatic modifications, which make them good candidates for use therapeutic. Shiau et al. (2022) provided a detailed understanding of the antiproliferative effects and mechanisms of fucoidans in oral cancer cells and demonstrated that fucoidans altered cell cycle progression, triggered apoptosis, activated intrinsic and extrinsic apoptosis signaling, stimulated oxidative stress, inhibited antioxidant signaling and improved DNA damage in oral cancer cells. According to Shiau et al. (2022) there is positive evidence to continue the research until to discover how these molecules can disrupt mechanisms of metastasis and multi-drug resistance in different types of cancer.

3.1.3. Laminarin

Laminarin is a storage glucan composed of 25–50 glucose units linked by β-1,3-glycosidic bonds and, in some cases, having β-1,6-glycosidic bonds and branches at the O-6 position. Laminarins are in the fibrillar cell walls and intercellular spaces of brown algae and can differ in the reducing end, which corresponds to a glucose residue in G-type laminarins and a mannitol residue in M-type laminarins, giving rise to different solubilities (Moroney, O'Grady, Lordan, Stanton, & Kerry, 2015; Stiger-Pouvreau, Bourgougnon, & Deslandes, 2016), Technologically, laminarin does not interfere with the formation of gels or viscosity and is completely dissolved in water at neutral pH. From a functional point of view, Neyrinck, Mouson, and Delzenne (2007) reported that laminarin has modulatory effects against systemic inflammation, decreasing the recruitment of inflammatory cells in the liver and reducing the expression of inflammatory mediators in the liver tissue. However, the biological activity of laminarins is still poorly researched but shows great future potential in food formulation.

3.2. Protein

According to Table 1, the protein content of brown algae can vary from 3 to 20.5% d.w. (Prabhasankar et al., 2009; Winarni et al., 2021). Brown algae proteins present all essential amino acids at levels close to those recommended by FAO/WHO (2007) with glycine, alanine, arginine, proline, glutamic, and aspartic acid corresponding to the largest fraction of amino acids, while tyrosine, methionine, and cysteine are found in smaller amounts (Lorenzo et al., 2017; Gressler et al., 2010), that can be limiting, as can be seen in Table 2. Compared to proteins of animal origin, those from algae have a lower biological value (Matanjun, Mohamed, Mustapha, & Muhammad, 2009); however, they can be used in the isolated form (only the consumption of algae) or associated with other plant and/or animal proteins.

3.3. Lipid

The lipid levels of brown algae are below 5% (Table 1); however, the lipid profile is very promising with the presence of omega-3 and omega-6 polyunsaturated fatty acids (PUFAs), with the predominance of eicosapentaenoic acids (EPA), docosahexaenoic acid (DHA) and arachidonic

Table 2
Amino acid profiles (g/100 g) of different brown algae.

Amino acid	*Undaria pinnatifia*	*Laminaria* sp.	*Hizikia fusiforme*	*Ascophyllum nodossum*	*Sargassum hemiphyllum*	*Sargassum henslowianum*	*Sargassum patens*	*Ascophyllum nodossum*	*Fucus vesiculosus*	*Bifurcaria bifurcate*	Adult recommendation[1]
Aspartic acid (Asp)	8.7	12.5	9.1	14.0	10.6	10.0	10.2	8.4	16.7	8.0	nd
Threonine (Thr)	4.4	3.5	4.1	5.1	4.0	3.7	4.1	3.6	6.2	3.6	23
Serine (Ser)	4.0	3.3	3.7	4.5	4.0	3.7	3.9	3.7	6.3	3.6	nd
Glutamic acid (Glu)	14.5	23.8	18.7	24.2	12.6	27.0	16.1	17.1	19.7	15.0	nd
Glycine (Gly)	5.1	4.0	4.8	5.6	5.6	5.2	5.2	4.2	6.5	3.9	nd
Proline (Pro)	3.6	3.1	3.8	nd	4.9	3.1	1.6	3.9	5.7	3.2	nd
Alanine (Ala)	4.7	5.7	4.3	6.0	7.5	5.7	6.5	6.5	9.8	8.5	nd
Valine (Val)	5.2	3.8	4.7	5.8	4.7	4.2	4.9	3.5	5.8	3.7	39
Methionine (Met)	1.7	0.9	1.6	nd	1.3	1.7	1.8	1.5	2.1	1.7	16
Cystine (Cys)	0.9	1.2	0.9	0.4	1.9	1.3	1.5	0.0	2.0	0.0	6
Isoleucine (Ile)	4.1	2.7	4.0	3.9	3.4	3.1	3.7	2.9	5.1	2.9	30
Leucine (Leu)	7.4	4.9	6.7	6.1	6.6	6.8	6.9	5.4	8.6	5.2	59
Tyrosine (Tyr)	2.9	1.7	2.8	2.7	2.9	2.8	3.1	1.6	3.2	1.7	nd
Phenylalanine (Phe)	4.7	3.2	4.6	5.2	3.8	3.9	3.7	3.4	5.4	3.3	nd
Histidine (His)	2.5	2.2	2.6	2.4	0.1	0.6	0.4	1.3	1.9	1.3	15
Lysine (Lys)	5.6	3.9	3.1	5.9	6.0	5.8	5.9	4.3	8.0	3.9	45
Arginine (Arg)	5.2	3.3	4.5	4.7	3.8	3.0	3.1	3.2	5.5	3.3	nd
Tryptophan (Trp)	0.7	0.5	0.4	nd	nd	nd	nd	nd	nd	nd	6
Total EAA[3]	nd	nd	nd	nd	34.6	33.0	35.5	nd	nd	nd	nd
Total AA[4]	87.3	86.5	90.9	nd	83.6	91.3	82.4	74.8	119.0	73.2	nd
Reference	Dawczynski et al. (2007)			Kadam et al. (2017)	Wong and Cheung (2001)			Lorenzo et al. (2017)			WHO/FAO[2] (2007)

[1] mg/g protein; [2] Mean nitrogen requirement of 105 mg nitrogen/kg per day (0.66 g protein/kg per day). [3] Total essential amino acids excluding tryptophan; [4] Total amino acids excluding tryptophan; nd = not determinad.

Table 3
Studies on the use of brown seaweed in different food groups.

Products	Seaweed	Application and concentration		Algae effect	Reference
Meat	*Himanthalia elongata, Undaria pinnatifida* and *Porphyra umbilicalis*	Low sodium meat gel/ emulsion	Algae powder at 2.5% and 5% concentrations.	↑ dietary fiber. ↑ hardness and chewiness and ↓ elasticity and cohesion. Improves the binding properties of water and fat.	Cofrades et al. (2008)
	Laminaria japonica	Breakfast sausages	Algal powder at concentrations 0, 1, 2, 3 and 4%.	↑ minerals. ↑ hardness, gummyness and chewiness. Improves cooking loss and emulsion stability in the 4% algae sample. Sample with 1% algae had higher scores for flavor, tenderness and juiciness.	Kim et al. (2010)
	Laminaria japonica	Patties	Algal powder at concentrations 0, 1, 3 and 5%.	↑ Moisture, minerals, carbohydrates, yellowing and elasticity. Samples with 1 and 3% algae showed improvement in cooking loss, reduction in diameter and thickness.	Choi et al. (2012)
	Undaria pinnatifida, Sargassum fusiforme and *Laminaria japonica.*	Frankfurters	Algae powder at 1% concentration.	↓ hardness, gummyness and chewiness of samples with reduced salt and algae content. ↓ cooking loss. ↑ tenderness, ↑ juiciness and general acceptability scores similar to control.	Choi et al. (2015)
	Ascophyllum nodosum, Fucus vesiculosus and *Bifurcaria bifurcata*	Pork liver pate	Seaweed extract, 5 formulations (control, with BHT, 500 mg/kg of each alga).	↑ protein. ↑ red/yellow color. Oxidation protection similar to BHT.	Agregán et al. (2018)
	Fucus vesiculosus, Ulva spp. and *Gracilaria* spp.	Sausages	Macroalgae mixture powder	↑ minerals. ↑ shelf life of products.	Marçal et al. (2021)
Dairy	*Ascophyllum nodosum* and *Fucus vesiculosus*	Fortified milk	Seaweed extract at concentrations 0.25 and 0.5%.	↑ yellowish/greenish color.The extracts were stable and exhibited varying degrees of antioxidant activity (DPPH and FICA) . Sensory associations of fish flavor and off-flavour.	O'Sullivan et al. (2014)
	Ascophyllum nodosum and *Fucus vesiculosus*	Yogurt	Seaweed extract at concentrations 0.25 and 0.5%.	↑ yellowish color ↓ lipid oxidation ↓ Sensory acceptability: color, flavor and texture were the most undesirable parameters.	O'Sullivan et al. (2016)
	Himanthalia elongata, Porphyra umbilicalis, Saccharina latíssima, Ulva lactuca and *Undaria pinnatifida.*	Yoghurt and quark	Algal powder at concentrations 0.25, 0.50, 0.75 and 1.0%.	↑ seaweed odor and flavor in yoghurts above 0.50%. The algae influenced the odor, taste and texture of the samples and sensory acceptance was dependent on the type and concentration of algae used. S. latissima showed the best sensory acceptance in relation to odor and flavor.	Nuñez and Picon (2017)
	Himanthalia elongata, Laminaria ochroleuca, Porphyra umbilicalis, Ulva lactuca and *Undaria pinnatifida.*	Cheese	Dehydrated seaweed powder at the rate of 10 g of seaweed per kg of curd.	↑ retention of whey. ↑ humidity and ↓ pH. ↑ yellowish color. Cheese flavor quality scores were negatively correlated with seaweed flavor.	Del Olmo et al. (2018)
Bakery and pasta	*Undaria pinnatifida*	Pasta dough	Algal powder at concentrations 0, 5, 10, 20 and 30%.	↑ protein, fiber and minerals. ↑ n-3 fatty acids. ↑ concentration of threonine, isoleucine, lysine and methionine. The 5% alga formulation was sensorially similar to the control.Samples with 10% had a higher acceptance rate (above 10% panelists complained of salinity) .	Prabhasankar et al. (2009)
	Ascophyllum nodosum	Bakery	Algal powder at concentrations 0, 1, 2, 3 and 4%.	All samples with 4% algae were sensory accepted. ↑ 4.5% dietary fiber content in breads with 4% seaweed compared to control. The incorporation of seaweed is the energy intake in a meal.	Hall et al. (2012)
	Ascophyllum nodosum	Gluten free bread	Algae powder at concentrations 2, 4, 6, 8 and 10%.	↑ volume using using algae in the range of 4 to 10%. ↑ antioxidant activity of bread. ↓ luminosity (~50 at control to ~33 with 10% algae addition).Overall sensory acceptability was better at the 2% (5.8) and 4% (4.8) concentrations.	Różyło et al. (2017)
	Fucus vesiculosus	Bakery	Algal powder at concentrations 2, 4, 6 and 8%.	↑ viscosity, density and firmness of the crumb. ↑ green color of the crust. The addition of up to 4% algae did not affect the bread's density and texture.	Arufe et al. (2018)
	Laminaria ochroleuca	Gluten free pasta	Seaweed powder at a concentration of 20%.	↑ fiber and minerals. ↑ firmness in the raw dough (5.8 N and 3.2 N in the control). ↓ firmness in the cooked dough (2.3 N and 2.8 N in the control).	Fradinho et al. (2019)

(*continued on next page*)

Table 3 (*continued*)

Products	Seaweed	Application and concentration		Algae effect	Reference
				↑ swelling, adhesiveness and extensibility. ↑ green color.	
	Ascophyllum nodosum and *Chondrus crispus*	Whole grain bread	Algal powder at concentrations 0, 2, 4, 6 and 8%.	↑ dietary fiber and ash. Breads with *A. nodosum* and *C. crispus* were acceptable at levels of 4% and 2%, respectively (dry, dense, strong and salty aftertaste affected the taste). ↑ density and dryness of breads.	Lamont and McSweeney (2021)
	Sargassum fulvellum, Enteromorpha linza, Codium fragile and *Hizikia fusiforme*	Cookies	Seaweed powder at 5% concentration.	↑ density ↑ thickness and ↓ diameter of the cookies. Lower sensory scores on seaweed cookies and were related to fish color, taste and smell.	Oh et al. (2020)
Juices	*Fucus vesiculosus*	Apple juice	Fucoidan at concentrations of 25, 100 and 1000 μg/mL were added to UHT apple juice.	It exhibited bacteriostatic and bactericidal effects against *L. monocytogenes* and *S. typhimurium*. 25–100 μg/mL was highly effective against both pathogens.	Poveda-Castillo et al. (2018)

Where: ↑: Increased; ↓: Decreased; BHT: Butylated Hydroxytoluene; UHT: Ultra High Temperature; DPPH: 2,2-Diphenyl-1-picrylhydrazyl; FICA: Ferrous-ion-chelating activity.

acid (ARA) (Lorenzo et al., 2017) lipid levels.

The healthy benefits of these PUFAs, DHA, and ARA have been shown in several epidemiological studies, where the omega-3 fatty acids had anti-inflammatory properties and were related to the prevention of cardiovascular diseases (DeFilippis, Blaha, & Jacobson, 2010), and had anticancer properties (Dimri et al., 2010). ARA also had an important role in biological systems, such as the immune response and brain function stimulation, and thrombosis prevention (Lee et al., 2010).

3.4. Vitamins and minerals

As an alternative to ensure adequate dietary vitamin intake, people (especially those on special diets, strict vegetarians, and vegans) can consume functional foods enriched with vitamins extracted from natural sources such as brown algae, because they contain vitamins A, B-complex, C, D, and E (Biancarosa et al., 2018), including vitamin B12, which is generally absent in vegetable foods. (MacArtain, Gill, Brooks, Campbell, & Rowland, 2007). Biancarosa et al. (2018) demonstrated that vitamin E ranged from 6.2 $mg*kg^{-1}$ in *Laminaria digitata* to 80.0 $mg*kg^{-1}$ in *Ascophyllum nodosum*. Algae are also sources of minerals, with contents ranging from 8% to 40% d.w. (Cofrades, Benedí, Garcimartin, Sánchez-Muniz, & Jimenez-Colmenero, 2017; Peñalver et al., 2020). The main minerals found are calcium (Ca), magnesium (Mg), potassium (K), iodine (I), sodium (Na), phosphorus (P), nickel (Ni), chromium (Cr), selenium (Se), iron (Fe), zinc (Zn) and manganese (Mn) (Gupta & Abu-Ghannam, 2011; Roohinejad et al., 2017).

The consumption of algae as a source of iodine has been reported (Correia et al., 2021) since iodine deficiency leads to problems in the population worldwide, causing malfunction of the thyroid gland and the production of thyroid hormones. On the other hand, excess iodine can negatively affect thyroid function, causing autoimmune disease, for example Hashimoto's thyroiditis (Wells et al., 2016).

Brown algae I_2 levels differ from species to species and have been identified as ranging from 0.16 to 7.53 mg/g d.w. (MacArtain et al., 2007). Therefore, knowledge of the iodine concentrations of algae to be used as a food source must be informed so that the consumer can adjust the diet of this mineral and consume algae safely.

In some countries, such as Brazil, iodine is supplemented in table salt (Brazil, 2003), but with its excessive consumption, as it is estimated that the population has a daily consumption of up to 5 times the daily requirement, since when salt is removed from the diet, in the case of diets for renal, cardiac and hypertensive patients, the consumption of I_2 drops dramatically (Campos et al., 2015), therefore, brown algae can also be an iodine source solution for special diets that need to supplement this mineral.

4. Bioactive compounds

Algae contain bioactive compounds, such as polyphenol phlorotannins and fucoxanthins (Cofrades et al., 2017). Phlorotannins are highly hydrophilic polymers from the tannin group, composed of phloroglucinol units (1,3,5-trihydroxy benzene), biosynthesized through the acetate-malonate pathway. They are typically found in brown algae at concentrations from 12 to 250 mg/g d.w. (Fletcher, Biller, Ross, & Adams, 2017) that depends on the location, time of year, and weather conditions. Concentrations of 14.9 mg/g d.w. and 5.9 mg/g d.w. were found in *Laminaria japonica* and *Undaria pinnatifida*, respectively, in a study in Japan (Machu et al., 2015).

Montero et al. (2016) analyzed that the phlorotannin composition of different samples of *Sargassum muticum* collected at different locations along the European Atlantic coast varied from 1.4 mg/g d.w. to 94.0 mg/g d.w. Mekinić, Skroza, Šimat, Hamed, Čagalj, and Perković (2019), in their review, showed that the phenolic content of several species of brown algae (from different geographic origins) varied. Also, analyzed the impact of experimental conditions (solvent, solid-solvent ratio, temperature, and extraction time) on their phenolic profile and demonstrated that the expression of results varies in the extraction protocols, which makes it extremely difficult to compare the results of different studies, which emphasizes the need to establish protocols.

Phlorotannins are associated with several functions, such as antioxidant activity against oxidation damage mediated by free radicals (Li, Wijesekara, Li, & Kim, 2011), and are also effective against some foodborne pathogenic bacteria, such as *Campylobacter* spp., *Staphylococcus aureus* and *Escherichia coli* (Besednova, Zaporozhets, Somova, & Kuznetsova, 2015; Poveda-Castillo, Rodrigo, Martínez, & Pina-Pérez, 2018). In their study, Kumar, Gunaseelan, Sangeetha, Arunkumar, Shakambari, Ashokkumar, and Varalakshmi (2022) showed that phlorotannin exhibited potent DPPH and nitric oxide radical scavenging activity *in vitro* and had a bioactive potential for diseases mediated by oxidative stress, such as diabetes and cancer.

Hermund (2018) indicated that phlorotannins can be used as a substitute for synthetic antioxidants in the food industry. Fucoxanthin is a class of thermostable pigments (Prabhasankar et al., 2009) and is among the carotenoids that are responsible for the specific color of brown algae (Gullón et al., 2020). Some reviews have shown that these pigments have properties similar to antioxidant, anti-inflammatory, immune-modulating, antidiabetic and antiangiogenic agents (Pangestuti & Kim, 2011; Brown et al., 2014; Déléris, Nazih, & Bard, 2016).

Peng, Yuan, Wu, and Wang (2011) reported that organic extracts of different edible algae inhibited the DPPH radical (1,1-diphenyl-2-picrylhydrazyl) and the fucoxanthin was the active compound, and Aryee, Agyei, and Akanbi (2018) indicated fucoxanthin for use as nutraceutical

ingredients and food coloring.

Fucoxanthins are also related to the reduction of cell damage induced by ultraviolet B (UVB) irradiation. Shi, Ren, Zhao, Zhu, and Qi (2022) used UVB-induced retinal Müller cells (RMCs) to screen dietary polyphenols and pigment compounds with effective photoprotective activity and *in vitro* results demonstrate that fucoxanthin provides a photoprotective effect, encouraging its use as a potential antioxidant supplement in functional foods for eye care. Furthermore, nano/microcapsules of fucoxanthins can be used to maintain their stability, increase bioaccessibility (Wang, Chen, Nakamura, Yu, & Qi, 2020), and expand their use in functional foods (Wang et al., 2021).

5. Consumption and application of brown algae

Brown algae have been identified as a renewable raw material with high added value, from which highly nutritious food products can be developed and used to reformulate existing products, remove, reduce, increase, add and/or replace different ingredients and/or additives and obtain products that confer health-promoting properties (Cofrades et al., 2017). The use of algae as a source of new natural antioxidant and antibacterial substances with a possible role as nutraceutical agents can contribute to both food quality and food safety (Polat et al., 2021).

Algae can be consumed as a vegetable in the diet and can be used in the same processing methods to preserve and/or improve the nutritive value and quality themes. In a study (Jiang et al., 2022) on the effects of different cooking conditions on the seaweed *Undaria pinnatifida*, the authors demonstrated that blanching and boiling were the best methods to reduce the loss of bioactive nutrients. Jiang et al. (2021) demonstrated that microwave cooking was the best method to preserve the color of algae. Both studies underscore that other cooking methods still need to be investigated.

Brown algae consumption is traditional in many Asian countries. In Japan, the average consumption is 10.4 g of fresh algae per person per day (Murai, Yamagishi, Kishida, & Isso, 2020), in South Korea, it is 8.5 g per day, and 5.2 g per day in China (Chen, Pan, Huang, & Han, 2018). In Europe, according to Araújo et al. (2021), up to 61% of the produced seaweed biomass is destined for the food industry, and they are used as ingredients in products such as bread, condiments, pasta, salads, snacks, soups, and supplements.

The safety of algae gained attention with its consumption increasing, then in 2019, the "Centre d'Etude et de Valorisation des Algues" formulated relevant laws and regulations based on an extensive analysis of the potential hazards of seaweed products, which may be related to the presence of excess iodine (Wu et al., 2022), heavy metals (Sevillano-Morales, Cejudo-Gómez, Ramírez-Ojeda, Cámara-Martos, & Moreno-Rojas, 2015), sulfur dioxide (Zhang et al., 2016) and even pesticide residues. Nowadays government agencies, food industries, and universities create new research areas to keep consumers safe when they eat algae and their food products.

In general, there is a lack of data on the availability and consumption of algae in the world's diet, with limited knowledge of consumers in Asian countries. Table 3 presents studies that used brown algae for the development of food products. The main results found for technological, nutritional, and sensory aspects showed a great expansion potential for algae in the world.

In addition to the studies presented in Table 3, algae can be used for the development of functional foods, since the bioactive compounds (already described in section 4, of this article) stay preserved during processing methods of food production.

5.1. Meat products

Some authors have shown that the addition of algae to meat products can improve the water-binding properties (Choi et al., 2012; Cofrades, López-López, Solas, Bravo, & Jiménez-Colmenero, 2008), but the main challenge is obtaining low-fat (Gullón et al., 2020) and low-sodium meat products (Gullón et al., 2021). When the sodium concentrations are decreased in meat products they promote worse technology due to lower protein solubilization, as heat-induced gels have weaker water and fat binding capacity. Some authors (Kim et al., 2010; Choi et al., 2015; Marçal, Pinto, Silva, Monteiro, Saraiva, & Cardoso, 2021), as can see in Table 3, reported that algae were a good substitute for sodium because they improve emulsion stability and retention of water and fat in sausages.

Table 3 shows that the addition of algae improved the nutritional profile of meat products and increased the mineral contents, dietary fiber, and antioxidant compounds by improving the nutritional profile of meat products (Agregán et al., 2018; Choi et al., 2015; Cofrades et al., 2008; Kim et al., 2010; Marçal et al., 2021). There is a growing interest in the food industry to replace synthetic antioxidants with natural antioxidants. Agregán et al. (2018) used brown algae as an antioxidant against lipid oxidation when compared to Butyl Hydroxy Toluene (BHT). At the end of the storage period, the authors reported that the algae showed protection against oxidation reactions, with a reduction of aldehydes, hydrocarbons, ketones, and alcohols.

The sensory aspects (Table 3) need to improve in meat products contain algae, because the consumers related an increase in the hardness and chewiness of meat emulsion (Cofrades et al., 2008) and, breakfast sausages (Kim et al., 2010), the authors related these results with the presence of dietary fiber.

There is increasing interest in physical methods such as irradiation combined with phenolic substances to improve fish gel properties in the food industry. Wang et al. (2021) demonstrated that phlorotannins extract can be used, in adequate dosage, as a natural gel enhancer to improve gel properties. He et al. (2020) demonstrated that riboflavin and brown algae polyphenol extract improved the properties of myofibrillar protein gel under UV irradiation and prevented quality deterioration caused by excessive gel oxidation.

5.2. Dairy products

Brown algae contain a variety of bioactive compounds and represent a potentially exploitable source of functional ingredients for the dairy industry. O'Sullivan et al. (2014) and O'Sullivan et al. (2016) studied the addition of brown algae extracts to milk and yogurt (Table 3), respectively, and reported that algae negatively affected sensory attributes such as odor, flavor, and texture, but promoted a significant decrease in lipid oxidation, which may have contributed to increased shelf life.

Nuñez and Picon (2017) (Table 3) supplemented yogurt and quark cheese with brown algae and reported that the effect on flavor, odor, and texture was dependent on the species and the concentration of algae, and the type of dairy product. Regarding the sensory characteristics of quark cheese, the differences caused by the addition of brown algae were partially masked, probably due to the richer fat and protein composition.

Del Olmo, Picon, and Nuñez (2018) (Table 3) reported that the physicochemical characteristics of cheese were affected by the addition of brown algae to the curd, showing a pH reduction and an increase in the whey retention capacity and the moisture content of the cheese.

5.3. Bakery and pasta products

The addition of brown algae to bakery goods generally aims to improve the nutritional characteristics, texture, and antioxidant capacity because they increase the minerals and dietary fiber contents (Fradinho et al., 2019; Hall, Fairclough, Mahadevan, & Paxman, 2012; Lamont & McSweeney, 2021; Prabhasankar et al., 2009). In gluten products, the algae can hinder the formation of a gluten network (Heiniö et al., 2016), affecting the processing, mixing, fermentation, and baking steps, as well as dough properties, such as viscosity and density, crumb color, and texture (Poutanen, Sozer, & Della Valle, 2014), but in gluten-

free products, the algae can promote a polysaccharide network with technological products, which can be seen in the works of Różyło et al. (2017) and Fradinho et al. (2019).

As shown in Table 3, products such as white bread (Arufe et al., 2018; Hall et al., 2012), gluten-free bread (Różyło et al., 2017), and whole wheat bread (Lamont & McSweeney, 2021) that were made with up to 4% algae substitution presented good sensory acceptance. In whole wheat bread, Lamont and McSweeney (2021) reported an improvement in sensory acceptance with an increase in the brown algae concentration, with a decrease in saltiness, dryness, density, and strong aftertaste, which are factors that impair the acceptance of the whole wheat products.

Fradinho et al. (2019) made gluten-free pasta with the addition of 20% algae in rice flour and their results promote nutritional benefits, such as energy value reduction, protein content, and insoluble dietary fiber increased.

Brown algae fibers (Table 1) are capable of increase water absorption and water retention in food products (Gómez-Ordóñez, Jiménez-Escrig, & Rupérez, 2010), and can be used as a source of dietary fiber and minerals in bakery products, including bread (Arufe et al., 2018; Hall et al., 2012), cookies (Oh et al., 2020), and pasta (Fradinho et al., 2019; Prabhasankar et al., 2009).

Różyło et al. (2017) studied gluten-free bread (Table 3) with the addition of 4, 6, 8, and 10% brown algae and found higher volumes than the control in all concentrations. According to the authors, the algae powder may have interacted with the other components of the formulation, and probably the protein content (6.6%) from brown algae contributed to improving the rheological properties of the dough, increasing the gas holding capacity and leading to an increase in the bread volume.

Prabhasankar et al. (2009) (Table 3) reported that the incorporation of algae (*Sargassum marginatum*) in bread formulations increased the gluten network of the dough by up to 2.5%, which resulted in improving the nutritional value, where the bread had better amino acid and fatty acid profiles showed the reduction of the *n-3* to *n-6* ratio from 1:15.2 to 1:3.4 and had a higher content of functional compounds such as fucoxanthin and fucosterol. The authors concluded that fucoxanthin was not affected by the manufacturing process and the cooking steps, which may be a positive aspect of the use of brown algae in bakery products.

5.4. Juices

Poveda-Castillo et al. (2018) investigated the specific bioactivity of fucoidan, an isolated compound of *Fucus vesiculosus* as a preservative in a pasteurized beverage marketed under refrigeration. The results showed the efficacy of fucoidan as a natural antimicrobial against *Listeria monocytogenes* and *Salmonella typhimurium*, opening new possibilities for using this natural compound as a bioactive ingredient for food preservation.

The development of brown algae containing food products (Table 3) is still a challenge due to the lack of knowledge about the industrial scale and the impact of algae on the overall appearance and sensory properties of these products.

6. Algae and sustainability

For many coastal communities, the extension of economic activities to the seas and oceans offers an excellent opportunity for growth and development (Prabhu et al., 2020). Brown algae could be a promoter of social inclusion with the development of new food chains, which could benefit all countries that have a coastal region focused only on fishing, generating great dependence on government aid by fishermen during the months of fish breeding, and in the pandemic, they had their source of income reduced by the absence of tourism in coastal regions.

The algae processing and commercialization chains will be able to supply the market with sources of fibers and bioactive compounds for the coastal population, which needs plant sources from elsewhere to supply these nutrients. Another important fact is that many algae-producing sites, such as in Chile, are planned to be close to fish and crustacean breeding sites, as their feces serve as fertilizer for their growth, expanding the development of circular processes of production (Camus, Infante, & Buschmann, 2019).

Therefore, brown algae play an important role in the preservation of coastal ecosystems, as they can reduce the cost of transporting plant foods off the coast, increase the use of fish feed, with the associated cultivation of fish and algae, promote other sources of income for the production surplus, and promote local valorization with greater environmental preservation, since by making the "sacred" environment capable of producing functional foods, programs to maintain hygienic-sanitary conditions will be created, preventing sewage, garbage and contamination by fossil fuel used in boats and ships contaminating the sea region; that is, our generation starts to play an active role in environmental sustainability, since algae are responsible for capturing over 55% of all the CO_2 produced in the world (Margalef, 1988).

That is, just as large forests, such as the Amazon in Brazil, are considered the lungs of the world, algae can be the lungs of the sea that could help in the fight against global warming, which has been on average in 2021 of 1.2 °C above the levels recorded between 1850 and 1900 (IPPCC, 2022), it soon becomes mandatory to create new paths that make food production more sustainable.

7. Final remarks and future perspectives

From an economic point of view, the increased use of seaweed can lead to the development of producers, local markets on the coasts of various countries, and environmental protection with the preservation of marine life around the coast.

From a technological point of view, the use of algae and their extracts has been effective in modifying the fat and texture profiles, preventing oxidative spoilage, and improving the nutritional value of various food products. However, there are still some challenges regarding sensory properties, which directly affect consumer acceptability. Knowledge of consumers' preferences and greater dissemination of the benefits of brown algae for human health is necessary for the inclusion of seaweed in the daily diet.

On the other hand, the nutritional and functional qualities of brown algae can contribute to an improvement of the human diet. The present review showed the use of algae in food processing. Advanced, but there are many opportunities for knowledge expansion, such as the phlorotannins from brown algae which have pharmacological potential against non-communicable diseases such as cancer and diabetes, and can be used in future research.

The trend is for research to intensify in the coming years, as the introduction of brown algae in food can meet the demand of the vegan, gluten-free public and consumers looking for healthier functional foods. However, currently, few studies quantify the chemical composition and the content of inorganic elements, being essential studies that aim to know the characteristics of each species of algae, of different geographic origins, to contribute with information that adds value as well as to identify the presence of potential hazards that could affect the safe consumption of seaweed.

Declaration of 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.

Data availability

Data will be made available on request.

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ARTIGO II (revisão)

Seaweed as a potential new source for starch, produced in the sea: A short review

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Seaweed as a Potential New Source for Starch, Produced in the Sea: A Short Review

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The social concern with sustainable development encourages the study of new sources of starch; among these sources, the cultivation of macroalgae is a strategy for the development of a sustainable bioeconomy. This mini-review aims to present the main aspects related to the current seaweed market, the extraction, composition, and properties of starch, as well as its prospects as a sustainable ingredient capable of generating income and health for the world's population. The green algae species *Ulva* has been suggested as a promising source for starch extraction; however extraction is a challenge mainly due to the difficulty in breaking down the cell walls and isolating the starch granules. The algal starch granule is small (1.7–7 µm), and another characteristic is the high amylose content, above 55%, which may indicate that it is a resistant starch or slow digestion. Seaweed starch still needs to be scaled its production, extraction, and application potential, as a main ingredient or as a co-product of gum processing, which already have a production chain, as they have great potential as nutraceutical or functional starch for food of low calorie, or for applications as a thickener in the food, cosmetics, and other industries.

Starch and its derivatives are the main sources of energy, accounting for more than 40% of the world's daily caloric intake,[1] and are also used in the food industry to thicken, texturize, gel, stabilize, and often replace higher-cost ingredients.[2] Starch production is predominantly carried out through traditional agriculture. Starch is extracted from sources such as corn, rice, wheat, potato, and cassava.[3] However, due to the increase in the world population and the growing need for food supply, guidelines on the sustainability of cereal production have been addressed,[4,5] as these commodities are produced in monoculture systems, with the application of fertilizers and pesticides, as they are very susceptible to crop pests.

Social concern for sustainable development encourages the study of new starch sources. The works of Zhu[6] and Tagliapietra et al.[7] presented several studies with regional starches, from fruits, seeds, and stems, among others, as a way to find new starchy sources preferably with competitive properties about those currently used, such as corn and potato starches, and chemically modified starches, for which natural substitutes are being sought, due to the demand for clean label products by the consumer.

Within this universe of starch production possibilities, there are some works, such as those by Yu et al.,[8] Prabhu et al.,[9] and Kazir et al.,[10] that began to highlight the starch of macroalgae, which becomes interesting, since the surface of planet Earth comprises approximately 70% water, with 97% of this water being in the oceans,[11] the natural habitat of macroalgae.

Macroalgae are a group of eukaryotic organisms, predominantly marine, multicellular, photosynthetic, containing chlorophyll "a," without true roots, stems, and leaves with simple reproductive structures and found from the intertidal zone to 300 m depth.[12] Macroalgae have high nutritional values, including proteins, essential amino acids, carbohydrates, lipids, dietary fiber, minerals, and antioxidants, which makes them excellent candidates for healthy food for human nutrition.[13] Seaweeds contain many types of bioactive substances with health-promoting properties, which include structural components such as alginate, carrageenan, and agar, as well as metabolic compounds such as β-carotene, eicosapentaenoic acid, phlorotannins, fucoxanthin, among others[14] and currently, it is already known that several bioactive compounds can be folded into starch, changing its nutritional function and turning it into bioactive compounds.

It is noteworthy that the cultivation of macroalgae is a strategy for the development of a sustainable bioeconomy, being an efficient practice to locally mitigate the acidification and deoxygenation of the oceans due to the ability of these organisms to absorb nutrients and carbon dioxide to grow.[15] Macroalgae are an important source of energy-rich reserve components that can be produced without compromising food supply chains in the future. In this sense, this mini-review aims to present the main aspects related to the current seaweed market, the extraction,

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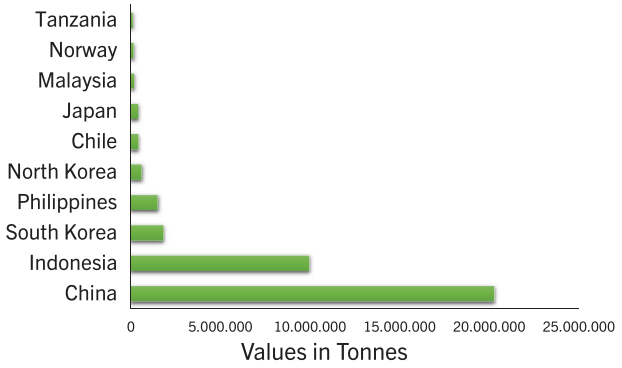

Figure 1. Top seaweed-producing countries (FAO, 2021).

composition, and properties of starch, as well as its future prospects as a sustainable ingredient capable of generating income and health for the global population.

A literature search was conducted on five databases: Web of Science, ScienceDirect, Scopus, Scielo, and Google Scholar. Studies published until 2022 were selected using the following search terms: "seaweed AND starch," "green algae AND starch," "red algae AND macroalgae," "macroalgae AND starch" on the title, abstract, and keywords. Only articles written in English about seaweed starch published in scientific journals were included. Another step involved the selection of data was the inclusion of official reports of international agencies (i.e., Food and Agriculture Organization—FAO).

According to the Food and Agriculture Organization of the United Nations,[16] 35.8 million tonnes of macroalgae were produced worldwide in 2019, with China and Indonesia representing almost 85% of this production (**Figure 1**). Most of the global production is cultivated, while a smaller fraction is collected from nature reserves.[17]

Algae cultivation has increased significantly in the last 50 years, with marine aquaculture being responsible for 96% of this production,[18] with 30.2 tons cultivated in 2016 in the world, 40.7% were tropical *Kappaphycus* and *Eucheuma* algae for the extraction of carrageenan; however, other species are cultivated and used for human consumption, such as *Porphyra*, *Undaria pinnatifida*, and *Gracilaria*, the most cultivated species, mainly for agar production.[19]

This growth in seaweed cultivation is mainly due to its rich composition in carbohydrates, proteins, fibers, and bioactive compounds of extreme importance for the human body, which are used in the food industry, and in the pharmaceutical, and the production of biotechnological compounds for the manufacture, for example, of renewable biofuels, which has been much researched and valued due to the possible future shortage of fossil fuels.[20]

Algae are valued for the extraction of their compounds; however, there is still a lack of attention to algal components, such as starch. Prabhu et al.[21] demonstrate that it is possible and advantageous to fractionate seaweeds and that when seaweeds are sold in fractions, there is greater added value. Thus, the extraction of starch is a way to increase the use of algae biomass, reduce waste and adverse environmental impacts, and maximize economic performance.

The green algal species Ulva has been suggested as a promising source for starch extraction.[10,22] Green algae starch is stored intracellularly in the form of granules ranging in size from 5 to 7 μm, found in round, oval, spherical, and irregular shapes.[22]

The process of extracting starch from macroalgae is crucial to obtain a material with an appreciable degree of purity. Variations in yield depend mainly on environmental factors (e.g., temperature and light intensity for starch synthesis), energy-demanding metabolic processes (cell division),[23] and extraction methods. In the scientific literature, there is a scarcity of studies reporting the isolation techniques of starch from this unconventional source. Previously, Prabhu et al.,[22] Prabhu et al.,[9] and Steinbruch et al.[24] used distilled water in a solid–liquid ratio of 1:20 w/v for the extraction of starch from *Ulva* sp. (green algae). The process continued with the steps of homogenization, filtration, centrifugation, washing with absolute ethanol, and drying. The neutral method resulted in purity of 50.37–59.54% starch,[9,22,24] demonstrating the potential for its commercial extraction.

In another study, Yu et al.[8] submitted *Gracilariopsis* sp. (red algae) grinding under liquid nitrogen with subsequent filtration, centrifugation, and sedimentation with distilled water to obtain the starchy material, is termed "Floridean Starch." Floridean starch, and is slightly different in its molecular structure from terrestrial plant starch, it is composed of an α-linked glucose polymer with an intermediate degree of branching between amylopectin and glycogen. Green algae starch, however, has the same molecular structure as terrestrial plant starch (only slightly smaller granules).

On the other hand, Kazir et al.[10] purified *Ulva ohnoi* starch with an alkaline solution (NaOH) 0.165% w/v to remove adherent proteins. It is necessary to emphasize that the type of isolation method used can affect the chemical composition, structure, and techno-functional properties of the starch.

Faced with current challenges and future needs, it is crucial to invest in more sustainable and circular production strategies. In this sense, the implementation of the circular economy (CE) is related to the adoption of practices for the maximum reuse of materials, goods, and components to reduce waste generation.[25] To assure circular and sustainable production strategies, it's important to grow the amounts utilized, and not to harvest natural wild algae, as this would dwindle the algae in the oceans (and with them many dependent fish and other species). Moreover, the cultivation practices should not cause environmental damage.

In this context, the extraction of starch from macroalgae can form a promising marine biorefinery; that is, other constituents generated during the starch isolation process (e.g., proteins, saccharides, lipids, phenolics, pigments) can be fractionated, purified, and destined for food and nonfood applications (**Figure 2**). In the case that starch is a coproduct, it is also necessary to direct it to other purposes and, consequently, to map the complete chain of macroalgae cultivation. In addition, there is a demand for new and emerging technologies due to the environmental impact of processing, as well as consumer demand for clean labels.[26]

In a previous study, Prabhu et al.[9] reported a pretreatment protocol for extracting starch from *U. ohnoi* via a pulsed electric field (PEF), a physical and nonthermal method with increasing industrial applications. The authors reported the ability of PEF treatment to increase starch extraction yield by 12% compared to untreated biomass.[9] Steinbruch et al.[24] reported that

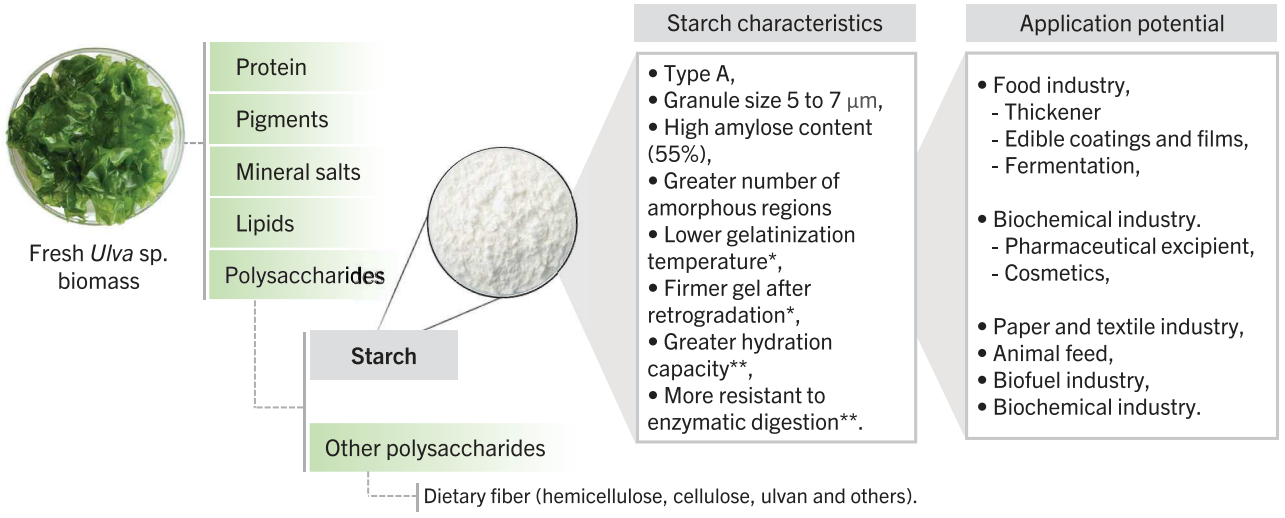

Figure 2. Lists the components, starch characteristics, and applications of products from fresh raw *Ulva* sp.

Table 1. Centesimal composition, on a dry base, of macroalgae starch.

Composition [g 100 g^{-1}]	Green			
	Ulva ohnoi	*Ulva ohnoi*	*Ulva ohnoi*	*Ulva* sp.
Starch	1.59–21.44	3.81	nd	5.7
Amylose	nd	nd	55.0	nd
Amylopectin	nd	nd	45.0	nd
Protein	0.08	nd	nd	nd
Ash	1.51	nd	nd	3.8
Lipids	2.43	nd	nd	nd
Reference	[21]	[20]	[10]	[23]

nd, not determined.

extracting starch from wet samples is more economically advantageous. However, this treatment to improve the extraction of starch from macroalgae was only carried out on a laboratory scale; therefore, studies involving energy consumption, installation projects, and combinations with other technologies are necessary, aiming at an industrial perspective.

Seaweed habitat is characterized by constant changes, which can influence species composition, resulting in seasonal variability in nutrient concentrations.[27] In addition, geographic location and site-specific conditions,[28] season, light, salinity, nutrients, temperature, pollution, water movement,[29,30] and biological state of algae[31] can impact their composition, directly affecting the starch extraction yield.

Table 1 presents studies that evaluate the proximate composition of starch from algae. Few compounds have been determined, and there are many gaps in the composition of these starches to be filled. Extraction is not challenging due to the small granule size, but mainly because of the difficulty in breaking cell walls and isolating the starch granules, which in *Ulva* is found in the chloroplast.[22]

Kazir et al.[10] found amylose levels 55% in *U. ohnoi* (green algae). The amylose content is affected by the botanical source and growing conditions,[32] the high amylose content may indicate that it is an RS or starch with slow digestion, with enhanced nutritional properties, as it can function as fiber and also carry bioactive compounds to be fermented in the colon, improving the health of the digestive system.

High amylose corn starch, also called "amylomaize," contains 70% or more amylose, but this type of starch was developed using genetic combinations,[33] unlike algae, which is found naturally. Starch with a high amylose content can be advantageous when developing foods with a low glycemic index, as it can lead to higher viscosity and higher gel strength upon cooling due to greater retrogradation, leading to lower digestibility.[34] In addition, the amylose content of starch influences the ability of starch granules to absorb water and affects starch solubility and gelatinization temperature.[32]

In contrast, the study by Yu et al.[8] who performed starch extraction from *Gracilariopsis* sp. (red seaweed) showed that the starch found showed only amylopectin, a starch called "Floridean starch." In addition to the absence of amylose, this starch has the characteristics of low gelatinization temperature, low viscosity, and little retrogradation[8] suggesting its application in the food industry in deep-frozen and instant products. Other paste (analyzed by Rapid Visco Analyzer—RVA) and gelatinization (analyzed by Differential Scanning Calorimetry—DSC) properties of algal starch were analyzed and are presented in **Table 2**.

The viscosity of the pastes is used to characterize the functionality of the starch and show changes during heating and cooling. The setback ratio (SR) was higher for *Ulva* (SR = 5.6)[10] than for Floridean starch (SR = 1.4),[8] demonstrating a greater tendency for *Ulva* starch to retrograde than for Floridean starch, and this is likely due to the high amylose content of *U. ohnoi* starch.[10] Another characteristic is the high swelling capacity (SC) of the *U. ohnoi* starch, which is higher than that of rice starch (10.3 g water g^{-1} starch).[35] The distinction between *Ulva* and *Gracilariopsis sp.* and the lack of more data on them point to the need for greater investments in research in this area. Figure 2, presents the potential of the process of extracting products from

Table 2. Starch properties of different macroalgae.

Properties		Seaweed				
		Ulva ohnoi	*Ulva ohnoi*	*Ulva* sp.	*Gracilaria lemaneiformis*	*Gracilaria chilensis*
Pasting properties	Peak time [min]	nd	~5	nd	3.8	nd
	Peak viscosity	nd	560 cP	nd	1547 mPa s	nd
	Final viscosity	nd	2300 cP	nd	1076 mPa s	nd
	Trough viscosity	nd	450 cP	nd	754 mPa s	nd
	Setback ratio	nd	5.06	nd	1.42	nd
Granule size [μm]		5–7	6.6	nd	1.7	3.4
Type		nd	A	nd	C and B	nd
SC		nd	25.7	nd	nd	nd
Gelatinization	T_0 [°C]	52	nd	nd	51.2	48.4
	T_p [°C]	118,4	nd	64	55.1	52.7
	T_c [°C]	126,7	nd	nd	60.0	57.1
	ΔH [J g^{-1}]	21,07	nd	nd	-11.19	-9.35
Reference		[21]	[10]	[23]	[8]	

nd, not determined; SC, Swelling capacity; SR, Setback ratio.

the fresh raw material, as well as the main characteristics of the starch from the alga *Ulva* sp.

In general, it is important to emphasize that the properties of algal starch still need to be investigated, the studies are still in an initial phase (on a laboratory scale) and large-scale applications are not found, however, due to the composition and characteristics of the starches (Table 2) potential to be used in the food industry (thickener, coatings and edible films, fermentation), biochemical industry (pharmaceutical excipient, cosmetics), paper and textile industry, animal feed and biofuels industry is perceived (Figure 2). In addition, an important characteristic for application in the food industry is the high amylose content found, which may indicate that it is a resistant or slow-digesting starch, with nutritional importance for application in low-calorie foods. RS obtained from plants are produced by genetic modification and are expensive, while starches from algae are natural. With the prospects of advancing research in this area, it will be possible to predict its functionality and suggest applications based on this information.

Macroalgae represent an alternative source of starch with great potential for exploitation due to their rapid growth rate, high productivity, possibility for off-shore cultivation, not requiring potable water, and use of arable land, in addition to having unique characteristics compared to commercial starches. The reason for investigating these new unconventional sources of starches is related to sustainability, zero waste, use of byproducts, availability, and technological advantages over common starches.

On the other hand, it is necessary to study and implement the concepts of a CE to promote a sustainable chain and increase the production of polysaccharides on a large scale, in addition to other constituents with high market value. In the future, scientists can help companies with projects to build photobioreactors to optimize production and think about integrative systems. Another future trend would be the use of genetic engineering techniques to sequence, express, and select genomes and, in this way, produce transgenic algae with high starch yields and better functionality. This opens avenues for research focused on overcoming the challenges associated with producing these biomacromolecules from conventional sources (e.g., corn, potato, and cassava).

There are many aspects related to the characterization of macroalgal starch that still need to be studied. The molecular structure (e.g., granule size distribution, amylose chain length distribution, amylopectin branched-chain length distribution) needs to be elucidated in detail. Furthermore, there is a lack of information on technological properties (e.g., solubility, swelling power, paste viscosity, gel texture, and syneresis). Furthermore, further efforts and research should be performed to compare the physicochemical, structural, and techno-functional properties of macroalgae starch from different locations with conventional sources. Regarding nutritional aspects, starch digestibility and glycemic index must be tested in food formulations.

The growing demand for macroalgae also implies the need for unified regulations that regulate the production and commercialization of any materials from this source. In the case of new food additives derived from algae, the established limits must be evaluated and authorized to guarantee the reliability of the starchy products. Toxicity studies (e.g., the presence of heavy minerals and other contaminants) should also be conducted to assess human health risks. Furthermore, government agencies can also promote projects to verify the feasibility of producing starch from macroalgae in small coastal communities. In addition, consumer perception and marketing strategies should be studied to encourage the integration of this material in the diet, as well as increase its acceptance in food matrices. Additionally, information campaigns on macroalgae are necessary for populations that have a low level of knowledge.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Keywords

food industry, marine biorefinery, sustainability, Ulva sp, unconventional starch

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ARTIGO III (revisão)

Rice (*Oryza sativa* L.) and its products for human consumption: general characteristics, nutritional properties, and types of processing

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Carta de aceite do artigo para publicação disponível no Anexo III

RICE (*Oryza sativa* L.) AND ITS PRODUCTS FOR HUMAN CONSUMPTION: GENERAL CHARACTERISTICS, NUTRITIONAL PROPERTIES, AND TYPES OF PROCESSING

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ABSTRACT

Rice (*Oryza sativa* L.) is one of the most important cereals globally, serving as an energy source for approximately 50% of the worlds population. In this review, we present and discuss the main aspects related to its characteristics, nutritional properties, and the types of processing carried out by the food industry. The nutritional composition of the grains varies according to the type of industrial process. After the husk is removed, both brown and polished rice can be obtained, and both types can also be parboiled. Products such as rice flour and starch have expanded the market for this cereal, as they are ingredients used in the production of various rice-based foods, owing to their hypoallergenic nature, gluten-free attributes, and mild flavor.

PRACTICAL APPLICATION

Encourage research, consumption by the population and safe and sustainable processing of rice.

KEYWORDS

Oryza sativa L.; processing; brown, polished, parboiling; nutritional quality; rice flour, starch.

1 INTRODUCTION

The dietary habits of the population have undergone significant changes in recent decades, especially concerning the rise in the consumption of processed foods. However, there are fundamental foods that continue to be a constant presence on consumers' tables, regardless of passing trends. A notable example is rice (*Oryza sativa* L.), whose consumption spans two-thirds of the global population, serving as a staple for about 50% of the population (FAO, 2022). Both its agricultural production and industrialization, as well as consumption, are undeniably the most important economic activity on the planet, as nearly half of the world's population consumes rice at least once a day (Wang et al., 2023).

For approximately half of this population, including various countries in Latin America, Asia, and the Pacific Islands, rice plays a crucial role as the main energy source in the diet (Zafar & Jianlong, 2023). This popularity is attributed, in large part, to the financial accessibility of rice, its ease and quick preparation, and its versatility, as it pairs well with various cooking methods (Das et al., 2023).

Rice not only feeds a large number of people but also constitutes the majority of the diet for many low-income individuals, making its nutritional value crucial in the diet (Bhattacharya, 2013). When consumed as polished rice, it is the primary source of starchy carbohydrates, providing quick energy when cooked and is widely consumed in main meals. It contains approximately 7% protein, while other nutrients are present in quantities below 1 - 2%, as shown in Table 1. In terms of minerals, rice offers a variety, including magnesium, phosphorus, calcium, as well as traces of iron, zinc, copper, and manganese (Verma et al., 2019).

However, the proportion of each nutritional component in rice is susceptible to various factors such as genetic variations, climatic conditions, fertilizer use, soil quality, processing, and storage (Zhou et al., 2002). This sensitivity can result in grains with distinct nutritional profiles (Fresco, 2005). Various post-harvest processing methods, such as polishing and/or parboiling, have the potential to impact the chemical composition of rice, leading to variations in measures relevant to nutrition. These variations, in turn, can affect the nutrient content in the diet.

In addition to consuming rice in its grain form, it is transformed into derivatives such as flour and starch, which are utilized by the food industry. Rice flour is gluten-free, making it a suitable alternative for individuals intolerant or sensitive to this protein (Qian & Zhang, 2013). In the food industry, it is used in gluten-free products such as bread, cakes, cookies, and pasta (Clerici & El-Dash, 2006). On the contrary, rice starch, is employed as a thickener, stabilizer,

and texture agent in a variety of food products. Its ability to form gels under specific processing conditions is suitable for enhancing the consistency and sensory quality of processed foods (Tong & Bao, 2018).

Considering this overview that underscores the relevance of rice, the objective of this review is to address the main aspects regarding its agronomic characteristics, nutritional properties, and the types of processing conducted by the food industry.

2 AGRONOMIC IMPORTANCE

Rice is an annual grass that encompasses 24 species of the Oryza genus, of which only two have become agronomically productive and important for human consumption: Oryza sativa of Asian origin and Oryza glaberrima of African origin (Vaughan, 1994). Of the two cultivated species, sativa is the most widely used and can be classified into three widely cultivated varieties:

- *Indica:* This is a long and slender grain used in tropical and subtropical Asia, South and North America. The high amylose content, associated with a lower amount of amylopectin, gives this variety a less sticky consistency (Wei & Huang, 2018). This variety has a firmer and glassy texture;
- *Japonica:* This is a short/medium and rounded grain, cultivated in temperate regions, such as like Japan and northern China. This type of rice provides a softer and stickier texture due to higher amounts of amylopectin, contributing to the adherence, a characteristic of the grains, and the opacity of the final product (Kowsalya et al., 2022; Wei & Huang, 2018);
- *Javanica:* Medium grains, cultivated in the Philippines and the mountainous areas of Madagascar and Indonesia (IRRI, 2013).

Currently, rice is cultivated in more than a hundred countries, producing around 500 million tons of paddy rice annually, distributed over approximately 165 million hectares (FAO, 2022). Across the world 93 million hectares of lowland irrigated rice fields provide 75% of global rice production (Lampayan et al., 2015). Some areas in South Asia, parts of Southeast Asia, and all of Africa use rainfed lowland agriculture, responsible for producing 20% of global rice. Upland rice cultivation under rainfed conditions accounts for 4% of the total rice production (IRRI, 2013). Given that 75% of production is under irrigation, rice is responsible for 30% of global irrigation water use, as well as 14% of fertilizers and 10% of pesticides (Grube et al., 2011; Heffer, 2013). In addition, it is a significant source of greenhouse gas

emissions, accounting for 30% of methane (CH_4) and 11% of nitrous oxide (N_2O) in global agriculture (IPCC, 2021; Linquist et al., 2012).

Brazil, which is ranked as the ninth-largest global producer, lags behind powerhouses such as China with 150.5 million tons, India, and Indonesia, as well as other prominent Asian countries (CONAB, 2021). In terms of production in South America, Brazil takes the lead, accounting for over 75% of the total production in Mercosur, surpassing Uruguay, Argentina, and Paraguay, respectively. The most prominent Brazilian state in this scenario is Rio Grande do Sul, leading production with an annual average of 8.1 million tons (CONAB, 2021).

3 RICE PROCESSING

Rice processing is a procedure aimed at separating rice grains from straw, husk, and impurities, resulting in final products ready for consumption. Various products are obtained from this process, with the main ones described below.

3.1 Brown Rice

Derived from the initial processing stage, after dehusking, brown rice retains the bran layer and germ (Figure 1). This gives brown rice a higher content of fiber, B-complex vitamins, and antioxidant minerals, and is considered a more nutritious option compared with white rice (X. Wu et al., 2023). However, it is more susceptible to degradation due to the presence of lipids and enzymatic activity (Lang et al., 2020).

In recent years, brown rice has shown an increase in consumption due to its nutritional and health benefits, such as reducing cardiovascular diseases (Ti et al., 2014), lowering postprandial glycemic response (Wu et al., 2013), inhibiting LDL-C synthesis due to its abundant oryzanol content and being associated with a reduced risk of type 2 diabetes mellitus (Imam et al., 2012). Despite this, brown rice is not widely consumed due to its lower culinary performance, rough texture (Ti et al., 2014), cost-effectiveness, and dietary habits of the population. These factors can be addressed by promoting the consumption of brown rice and its inclusion in basic food baskets, school meals, hospital meals, and popular restaurants, with subsidies and training for handlers who can make it more palatable to consumers, reviving the habit of its consumption, which was lost with industrialization.

Recently, RDC No. 712, dated July 1, 2022 (ANVISA, 2022), established labeling requirements for foods to be identified as whole foods. It was established that for this expression to be highlighted on product labels, it needs to contain a minimum of 30% whole ingredients,

and the quantity of whole ingredients must exceed the quantity of refined ones, which can be an incentive for the use and increased consumption of whole grains.

When focusing on sustainability in food production and environmental benefits, it is essential to highlight that brown rice production can be more sustainable, as it requires fewer processing steps (Figure 1), resulting in lower consumption of water and energy compared with the rice polishing process (Figure 2), which requires more steps and inputs, and also yields a higher amount of whole grains.

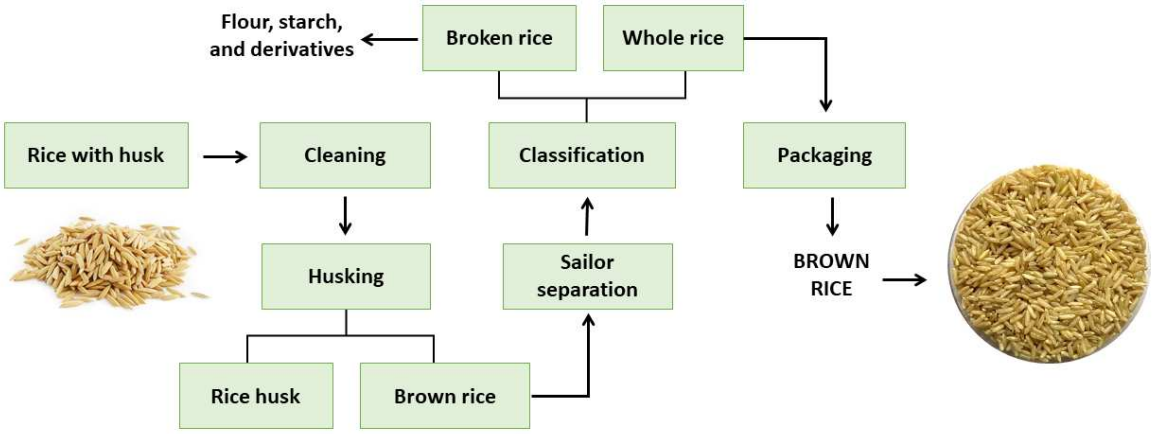

Figure 1. Conventional brown rice processing process.

3.2 Polished White Rice

White rice is a significant source of starch and carbohydrates, being the most common and consumed form of rice in many cultures around the world (Oliveira; Amato, 2021). The conventional process (Figure 2) involves cleaning, dehusking, separating paddy grains (grains that remained with husk are separated from dehusked ones based on density difference), followed by milling (the stage where the pericarp and germ, which transform into bran, are removed) and polishing, with the purpose of enhancing the final appearance of the product, giving it a glossy and scratch-free look (Ferreira et al., 2020). After these stages, the rice is classified, where broken grains are separated and subsequently categorized, as per Brazilian regulations.

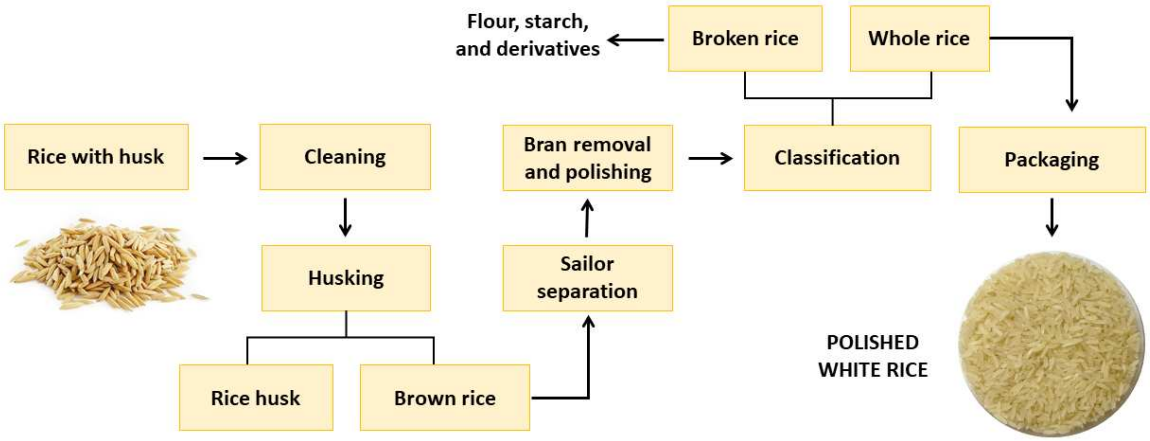

Figure 2. Conventional process of polishing white rice.

Normative Instruction No. 06, dated February 16, 2009 (Brasil, 2009), classifies grains into three classes:

- Long slender: grains with a size equal to or greater than 6 mm;
- Long: grains with a size greater than 6 mm;
- Medium: grains with a size smaller than 6 mm and greater than 5 mm;
- Short: grains with a size smaller than 5 mm. Grains with a size smaller than 4.49 mm are classified as broken.

In this classification stage, grains with defects (chopped, stained, damaged, and scorched grains) are also removed using optical sensors for identification and separation based on color, where grains with a different color from the standard are separated from the rest (Lang et al., 2020). Subsequently, packaging is carried out, and is considered the finalization of the industrial process.

3.3 Parboiled Rice

The parboiling process is a pre-cooking technique for rice grains while still in the husk before undergoing traditional processing to become white rice. As illustrated in Figure 3, this method involves three main stages: hydration, steaming, and drying.

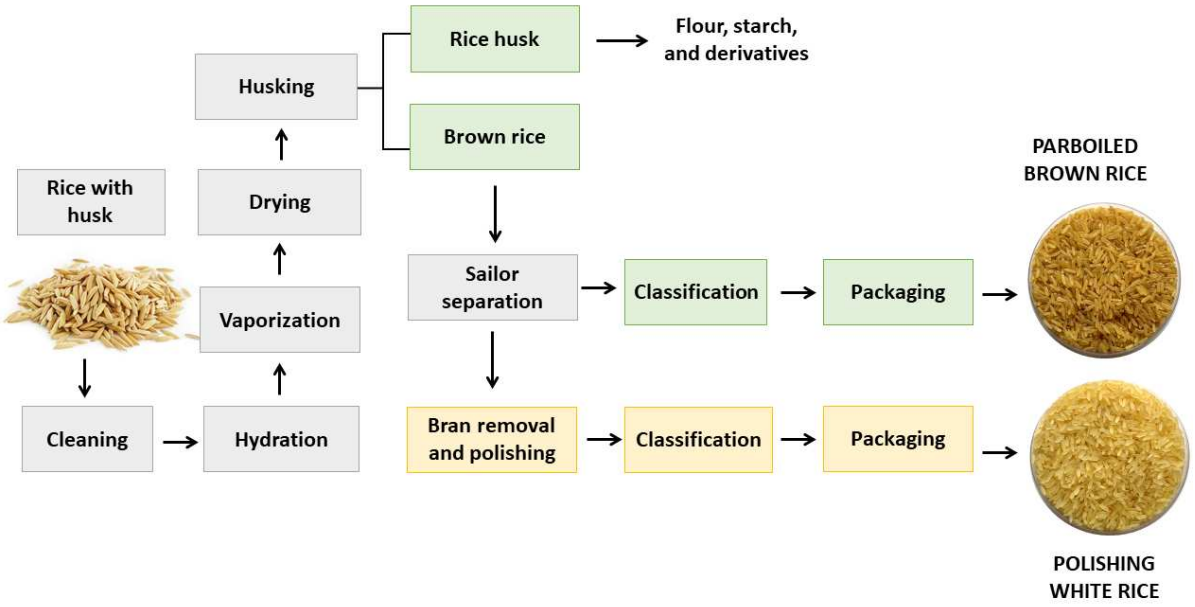

Figure 3. Conventional parboiling process of brown and white rice.

The hydrothermal parboiling process involves the following operations (Lang et al., 2020), as demonstrated in Figure 3 and described below:

- *Hydration:* The husked grains are immersed in hot water, around 60 to 70°C for several hours (4 - 7 hours). Water is absorbed by the grains, increasing their moisture content (optimal moisture for parboiling is 30%). Temperatures above 60°C discourage the enzymatic activity of α-amylases, which is responsible for breaking starch chains and increasing reducing sugars, causing darkening via the Maillard reaction (Oliveira & Amato, 2021).
- *Steaming:* After immersion, the moist grains are subjected to steaming. They are exposed to high-pressure water vapor. The heat from the steam penetrates the grains, causing the gelatinization of the starch in the endosperm. Gelatinization transforms starch into a firmer form resistant to overcooking.
- Drying: Parboiled grains undergo a drying process to remove the moisture acquired during hydration and steaming, aiming to reduce the moisture to an optimal level for processing (about 13%) and inhibit the growth of microorganisms and insects.

After completing these stages, parboiled rice grains are dehusked and polished, transforming them into white grains ready for consumption.

The advantages of the parboiling process include minimizing grain breakage during processing, increasing the yield of whole grains, resistance to pests and moisture, and non-

clumping, resulting in lower solid loss (Bhattacharya, 2013). The grains absorb more water during cooking, increasing volume (Lang et al., 2020). There is partial or total inactivation of enzymes, eliminating biological processes such as germination and fungal growth (Bhattacharya, 2013).

It is worth noting that the parboiling process not only alters the texture of rice, making it more resistant to breakage during cooking but also preserves some nutrients that would normally be lost during the processing of white rice. On the contrary, the disadvantages of the parboiling process include the development of aroma and flavor, the possibility of fermentation due to soaking, solubilization of albuminoids due to maceration time, and high temperature (Bhattacharya, 2013).

4. STRUCTURE AND CHEMICAL COMPOSITION OF GRAINS

4.1 Grain Structure

Understanding the morphological characteristics of the grain is essential for comprehending the physical and chemical properties of rice grain (Walter et al., 2008). Also known as a caryopsis, the grain consists of the pericarp, endosperm, and embryo or germ, enclosed by a non-edible husk that is hard and siliceous, consisting of two modified leaves, the palea and lemma (Juliano & Tuaño, 2019) (Figure 4).

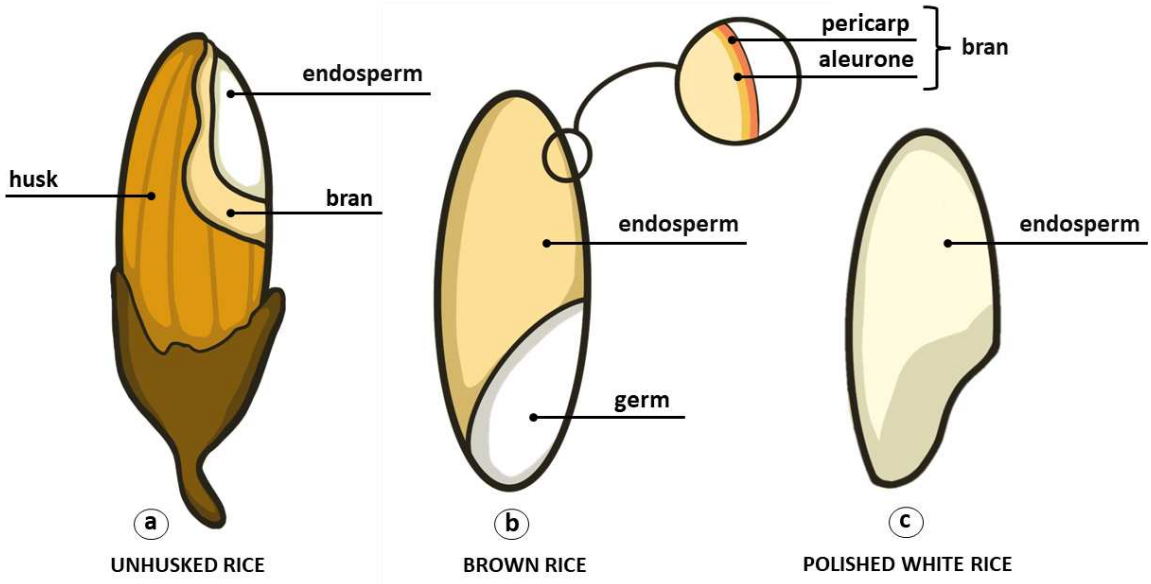

Figure 4. Morphological characterization of rice grain in husk, brown, and polished white.

From Figure 4, it can be observed that the rice husk protects the caryopsis (grain) and has been associated with the grain's resistance to insect infestation during storage, besides shielding it from primary pests. Rice husks stored under controlled humidity conditions can be stored for years. The outermost layers, namely, aleurone and pericarp, exhibit the highest concentrations of proteins, lipids, fibers, minerals, and vitamins, while the endosperm consists of starch and proteins, and the germ is the region with the highest lipid concentration (Juliano & Tuaño, 2019; Walter et al., 2008).

4.2 Nutritional Composition

The composition varies according to the type of industrial process. The processing operations, discussed in the subsequent section, may involve the extraction of the germ and bran, resulting in decreased levels of proteins, lipids, and minerals (Kowsalya et al., 2022).

Carbohydrates make up about 75 to 80%, with starch representing approximately 90% of these, which is the predominant component, accompanied by fibers and free sugars such as fructose, raffinose, and glucose (Arsha et al., 2021). The endosperm is composed of starch and proteins, while the bran contains fibers and the germ contains lipids, with small amounts of other types of carbohydrates (Walter et al., 2008).

Starch is a polysaccharide composed of amylose and amylopectin chains. The ratio of these chains varies among different genotypes, allowing the classification of grains into categories such as waxy (99% amylopectin), very low amylose content (2 - 12%), low (12 - 20%), intermediate (20 - 25%), and high (25 - 33%) (Juliano & Tuãno, 2019). The amylose content is a parameter used to determine the technological and consumption quality of rice. Generally, grains with higher amylose content exhibit a firmer texture after cooking, being preferred in various regions, including Brazil. However, other factors such as the structure of amylopectin chains and protein content also influence this characteristic (Ong & Blanshard, 1995).

The metabolic response during rice consumption is related to the amylose and amylopectin ratio, as a higher amylose content in rice, as well as in other starchy foods, is associated with a lower glycemic and insulinemic response (Miller et al., 1992). These physiological variations are of significant interest in the prevention and treatment of diseases such as diabetes, as a reduction in carbohydrate digestion and absorption contributes to maintaining regular blood glucose levels (Mahan et al., 2013).

Table 1 presents the nutritional composition of different types of rice, where it is observed that, in general, the highest carbohydrate levels are found in polished rice.

Table 1. Nutritional composition of different types of rice.

Types of rice	Composition (g/100g b.s.)[1]					References
	Carbohydrates	Dietary fiber	Protein	Lipids	Ashes	
Polished White rice	87.53	2.87	8.94	0.36	0.30	Denardin et al. (2014)
	83.70	nd	10.76	2.76	1.21	Yuliana & Akhbar (2020)
Polished parboiled rice	85.08	4.15	9.44	0.69	0.67	Denardin et al. (2014)
	81.07	4.18	10.73	1.07	1.24	Fagundes (2010)
Brown rice	74.12	11.76	10.46	2.52	1.15	Denardin et al. (2014)
	73.22	10.14	8.09	1.82	1.14	Saleh et al. (2019)
Parboiled brown rice	80.00	6.67	9.65	3.90	nd	Amostra comercial

[1] Data transformed from wet to dry basis from the sources consulted, for comparison. b.s = dry basis. nd = not determined.

The protein content of rice can vary depending on the type of processing employed (Table 1), as well as the cultivation method, nitrogen fertilization, solar radiation, and temperature during grain development (Walter et al., 2008). The main proteins found in rice are prolamins and glutelins. Similar to other cereals, rice has lysine as the limiting amino acid and significant amounts of cysteine and methionine. Nutritionally, the combination with beans (2:1) provides all essential amino acids to the body. In this context, identifying cultivars with higher protein content may be relevant to develop strategies aimed at reducing protein-energy malnutrition. Furthermore, to improve the amino acid profile, research has been conducted to increase the concentration of certain amino acids, such as lysine, methionine, and cysteine, through genetic modification (Zafar & Jianlong, 2023).

The lipids in rice are predominantly composed of triglycerides, phospholipids, and free fatty acids, deposited mainly in the germ (one-third of the total germ) (Tong & Bao, 2018). As brown rice has a higher lipid concentration (Table 1), it is more susceptible to lipid oxidation than polished white rice, which has reduced lipid content due to polishing. Regarding fatty acids, 95% of the composition is represented by palmitic acid (16:0), oleic acid (18:1), and

linoleic acid (18:2), which play important roles in various physiological processes and, as they are not synthesized by the body, need to be ingested through the diet (Walter et al., 2008).

Although lipids constitute a small proportion of rice compared with other elements such as carbohydrates and proteins, they play an important role in determining the taste and nutritional value of rice, as they have a significant correlation with sensory attributes (Park et al., 2012). Additionally, changes in the fatty acid profile are the main factor affecting aging during grain storage, as lipids undergo oxidation and degradation under the action of endogenous and microbial lipases during storage, resulting in a deterioration of taste and palatability (Tong & Bao, 2019).

Minerals are present in the rice grain mainly in the outer layers; consequently, whole grains have a higher mineral content compared with polished ones. In the husked grain, silicon is the dominant component, while in whole and polished grains, phosphorus, potassium, and magnesium stand out (Walter et al., 2008). The mineral content is influenced by cultivation conditions, geographical region, and processing (Du et al., 2013). For example, in parboiling, minerals in the aleurone layer (Figure 1) are solubilized in water and migrate from the outer layer of the grain to its interior (endosperm), resulting in an increase in mineral content (Lang et al., 2020).

Rice mainly contains B-complex vitamins and α-tocopherol (vitamin E), and like minerals, the highest concentrations are available in the outer part of the grain (Walter et al., 2008). Both for vitamins and minerals, biofortification emerges as an effective process to increase the levels of micronutrients present in rice and is a sustainable and viable strategy to alleviate micronutrient deficiencies in less privileged people with limited access to the food market (Ghosh et al., 2019; Paine et al., 2005). Among these research efforts, one of the main focuses is to increase the carotenoid levels in rice grains (Endo et al., 2019; Paine et al., 2005) through the combination of molecular biology and genomic approaches. Bai et al. (2016) managed to increase the total carotenoids up to 25.83 μg/g through genetic modification.

Another important component is the bioactive compounds present in rice, which are mainly found in the form of phenolics, divided into phenolic acids, flavonoids, condensed tannins, lignins, and lignans (Soto-Vaca et al., 2012). Phenolics are synthesized in rice plants in response to ecological and physiological stresses, such as pathogens, insects, and ultraviolet radiation (Park et al., 2012). Depending on the grain color, i.e., the variety, different concentrations and compounds may be present. For example, anthocyanins are the main pigment responsible for the black and red color of rice grains (Kowsalya et al., 2022) and show

a higher concentration of bioactive compounds compared with white rice varieties. Bioactive compounds have gained increasing attention due to their known physiological functions, as they can exert antioxidant effects and help prevent cellular damage (Ryan, 2011).

Most rice is consumed in the form of cooked grains, but it has other uses, such as bran in animal feed, oil extraction, obtaining flour, and starch for use in food and pharmaceutical products. The next section discusses functional and technological properties, focusing on rice flour and starch used in baking and extruded pasta, among others.

5. CONSUMER PRODUCTS

5.1 Rice Flour

Rice flour, obtained from finely ground rice, plays a crucial role as a fundamental ingredient in the production of various rice-based foods, including noodles, bread, cakes, among others (Rosell et al., 2021). Due to its hypoallergenic nature as a raw material and its white color and mild flavor, rice flour has seen significant expansion in its use (Baxter et al., 2014). The current trend emphasizes the development of an increasing variety of products incorporating rice flour, with the expectation of exploring more versatile manufacturing processes for the inclusion of new raw materials.

Rice flour can be produced from whole or broken rice grains (Tavares et al., 2012). In the context of sustainability, it is noteworthy that rice flour produced in Brazil is derived from broken rice, a by-product of the polishing of white rice, characterized by lower commercial value (Nabeshima & El-Dash, 2004). Valuing local production and expanding its use are fundamental factors in this scenario, considering that approximately 14% of rice grains are broken during milling processes (Castro et al., 1999).

Rice flour has several benefits and has found applications in various products, especially for patients with celiac disease, who are allergic to gluten, which is a wheat protein. Its non-allergenic nature represents a significant reason for the growing adoption of rice flour in the food industry (Kadan et al., 2003) (Figure 5).

The quality of rice flour depends greatly on the chemical profile inherent in each sample and also on its preparation method and the degree of gelatinization (Amagliani et al., 2016). For example, waxy rice flour is used in the food industry as a thickening agent for sauces and puddings, as it can prevent syneresis when these products are frozen, stored, and subsequently thawed, providing notable stability and versatility in culinary applications. Baby foods, beer,

and breakfast cereals are mainly produced with low amylose (12 - 20%) and intermediate amylose (20 - 25%) rice is used for noodle production (Bao & Bergman, 2018).

5.2 Rice Starch

Starch, constituting between 72% and 82% of the dry weight of the whole rice grain, emerges as the predominant composition in the grain (Biduski et al., 2018; Frei et al., 2003). Its main components are amylose and amylopectin, with amylopectin being a highly branched molecule with branching points through α-(1,6) linkages and generally representing 65% to 85% of the matter in starch granules. On the contrary, amylose is composed of glucose molecules linked by α-1,4 in long chains, with some α-1,6 branching points (Bao, 2019). Its linear nature confers unique properties, including the ability to form complexes with iodine.

The distinction between rice starch and flour lies in the removal of most proteins and lipids native to flour, resulting in a protein content in isolated rice starch generally of 0.5% or less. The interest in using rice starch is due to its mild flavor and creamy appearance in its gelatinized form and the small size of its granules, ranging from 3 to 8 μm (Bao & Bergman, 2018). This interest is mainly focused on the food industry as ingredients in desserts, baked goods, breakfast cereals, baby food and hypoallergenic foods (Figure 5), and is also used as a fat substitute (Colussi et al., 2015).

The functional properties of rice starch, described below, play a crucial role in its final use (Bao, 2019).

- *Swelling Properties:* The starch granule swells several times its initial size as a result of the loss of crystalline order and water absorption inside the granular structure;
- *Thermal Property:* Gelatinization, evidenced by irreversible changes such as granular swelling, loss of birefringence, and starch solubilization, is determined by differential scanning calorimetry (DSC), which measures gelatinization parameters such as onset, peak, and end temperatures, as well as the gelatinization enthalpy (ΔH). This property is essential for determining the rice cooking temperature;
- *Retrogradation Property:* A process in which a heated starch paste cools below the melting temperature of starch crystallites, resulting in increased viscosity, hardening of the gel, and texture. Amylose and amylopectin associate with swollen starch granules, contributing to long-term rheological and structural changes;
- *Starch Digestive Property:* Starch can be categorized as rapidly digestible (RDS), slowly digestible (SDS), and resistant (RS). AR is positively correlated with the amylose

content in rice starch, while SDS decreases with increasing amylose content. SDS and RS are related to a slow increase in postprandial blood glucose levels over time compared to RDS, which is advantageous for satiety and diabetes control. Therefore, SDS is the most desirable type from a nutritional standpoint.

These characteristics highlight the relevance of rice starch in culinary applications and its implications for human health.

Figure 5. Products derived from rice flour and/or rice starch available in the market, namely: a) Whole grain rice pasta; b) Rice pasta; and c) Whole grain rice biscuit.

6 RESEARCH AND FUTURE TRENDS

Rice has been studied worldwide, with over 100,000 scientific publications in the last 10 years (SCOPUS, 2023). Figure 6 presents a network visualization map of publications on rice and nutritional quality from the last 10 years (2014 - 2024), where each color represents a cluster. During this period, 1524 scientific articles were found, which were divided into five areas of interest involving nutritional value (red), human consumption (green), micronutrients (blue), animal feed (yellow), and consumer attitudes and perception (purple) (Figure 6a). Most of these studies were conducted in Asian countries, led by China and India, followed by the United States and Brazil (Figure 6b).

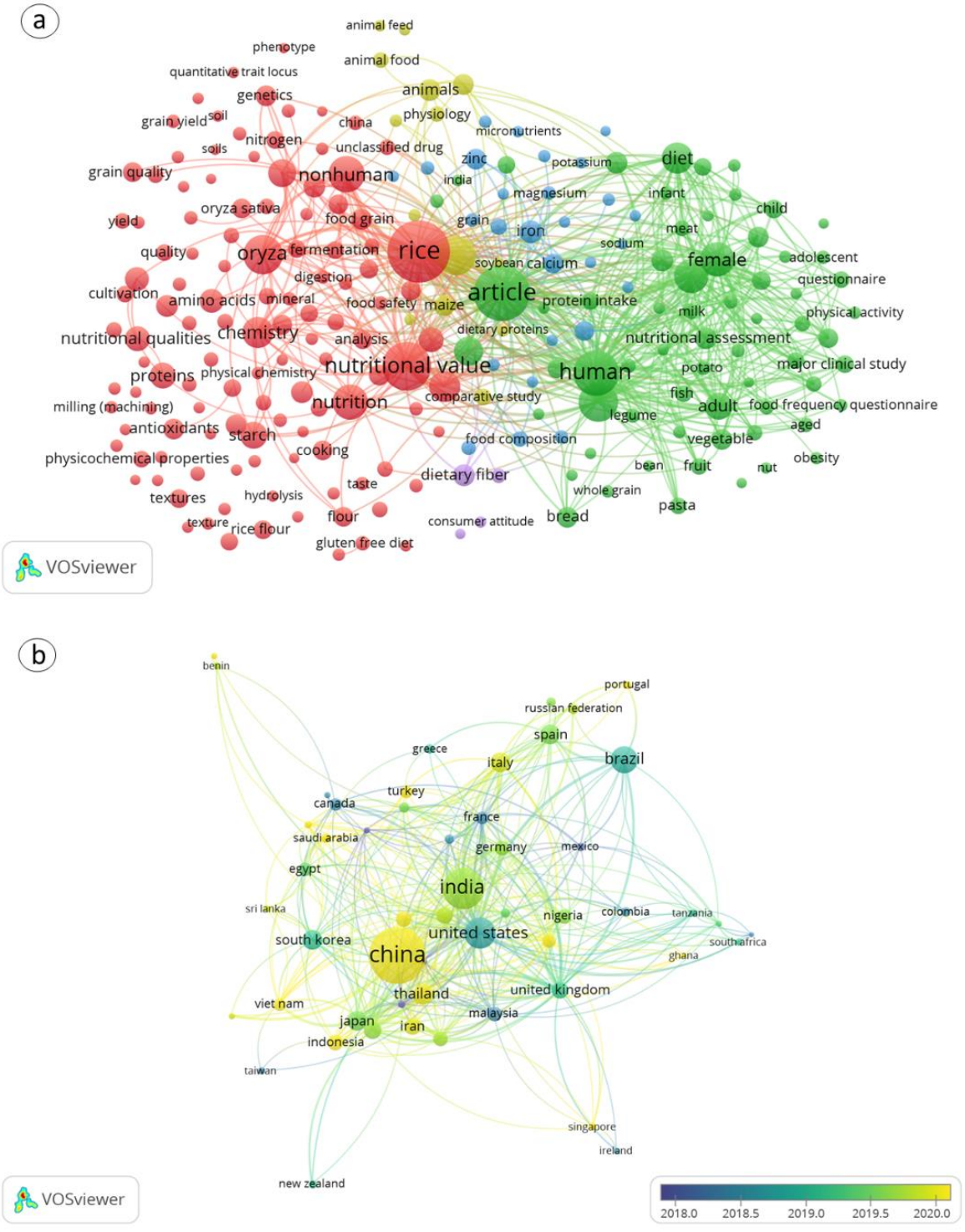

Figure 6. Network visualization map of publications on rice and nutritional quality, namely: a) co-occurrence keyword clustering and b) country co-authorship from 2014 to 2024. *Representation obtained through VOSviewer software version 1.6.19, with data obtained from a search conducted on SCOPUS (December 2023) using the equation TITLE-ABS-KEY ("rice" AND "nutritional quality").

7 GENERAL CONSIDERATIONS

Rice and its derivatives already have a consolidated potential as an ingredient in the food industry, offering improvements in the nutritional, technological, and sensory aspects of various products. However, continuing to promote and expand research that deepens nutritional composition is essential to determine potential health benefits. It is important to analyze the effects of processing on the nutritional and techno-functional characteristics of products based on rice flour or starch. This approach can promote the development of derivatives with higher added value, such as snacks with the addition of industry by-products or new ingredients, bakery products, and an ingredient of extreme importance to the industry due to the absence of gluten, which can create business opportunities, product innovation, and market expansion, benefiting both consumers and the food industry.

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ARTIGO IV (research article)

Nutritional and techno-functional properties of the Brazilian seaweed *Sargassum* sp.

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NUTRITIONAL AND TECHNO-FUNCTIONAL PROPERTIES OF THE BRAZILIAN SEAWEED *Sargassum* sp.

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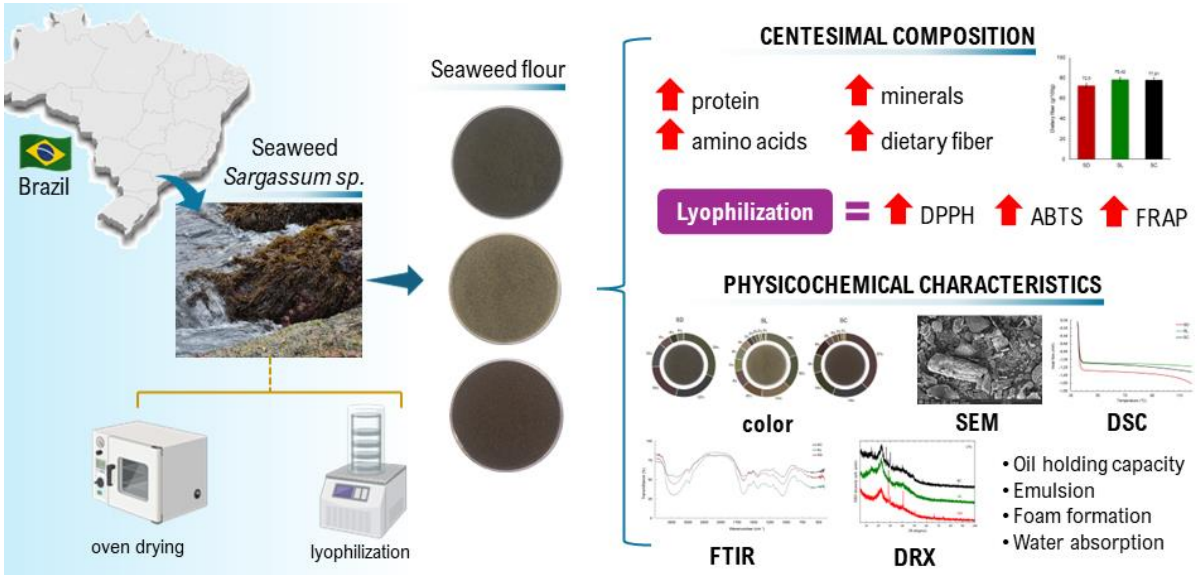
GRAPHICAL ABSTRACT



HIGHLIGHTS

- The seaweed flours dried in the oven and lyophilized exhibited significant differences in composition.
- The seaweed flours are rich in dietary fibers, with contents exceeding 70%.
- Seaweeds are sources of essential amino acids, such as lysine, and non-essential ones, such as glutamic and aspartic acids.
- Oven drying (SD) appears to elevate the amorphous cellulose fraction in XRD diffractograms, contrasting with lyophilization (SL), corroborated by SEM images displaying better-preserved fibers in SL.
- Lyophilization better preserves the antioxidant properties and phenolic compounds of seaweeds.
- Seaweed cultivation offers economic opportunities for coastal communities.

Nutritional and techno-functional properties of the Brazilian seaweed *Sargassum* sp.

ABSTRACT

With the increasing need to promote healthy and sustainable diets, seaweeds emerge as an environmentally friendly food source, offering a promising alternative for food production. The aim of this study was to characterize the brown seaweed *Sargassum* sp. from the coast of São Paulo, Brazil, regarding its nutritional and techno-functional properties using two dehydration methods, oven drying (SD) and lyophilized (SL). A commercial dried sample (SC) was used as a control. Analyses of proximate composition, mineral determination, amino acid determination, antioxidant capacity (DPPH, ABTS, FRAP, and total phenolic content), pH, color, scanning electron microscopy (SEM) imaging, X-ray diffraction, thermal properties by DSC, Fourier-transform infrared spectroscopy (FTIR), and techno-functional properties were performed. Seaweed flours (SD, SL, and SC) showed significant differences in physicochemical composition, with dietary fiber content of seaweed flours exceeding 70%. Glutamic and aspartic acids were the most abundant amino acids, with contents of 88.56 and 56.88 mg/g of protein in SD, respectively. Both for antioxidant potential and bioactive compounds, SL flours showed the highest levels of compounds. SL exhibited lighter color compared to SD and SC. Emulsion formation, foam formation capacity and stability were higher in SL, as well as water and oil absorption. The results suggest that seaweeds can be used to formulate a wide variety of food products, such as sausages, bread, cakes, soups, and sauces.

KEYWORDS: Brown seaweed; Seaweed proteins, Drying, Proximal composition, Nutritional security, Antioxidants.

1 INTRODUCTION

In recent years, the consumption of seaweed has gained popularity in countries where its consumption was not traditional, mainly as a food ingredient, with the aim of improving the nutritional properties of foods. For example, they can be used to increase dietary fiber intake (Peinado et al., 2014). This recent practice is motivated by the improved understanding of seaweed properties, clarification of their nutritional value (Afonso et al., 2019; Gullón et al., 2020; Ismail et al., 2023) and health benefits, such as prevention of non-communicable chronic diseases, improvement of microbiota, immunomodulation, dyslipidemia control, hypertension control, diabetes, and some types of cancer (Ismail et al., 2023).

Economically, seaweeds already exist and are consumed, but the challenge lies in developing productive chains in coastal countries not yet accustomed to their consumption, which can generate employment and income, as already exists for shrimp, fish, oysters, among others. Therefore, they should be seen as a sustainable alternative since they can be cultivated in seawater (Araújo et al., 2021; Véliz et al., 2022). Among the three groups of macroalgae, brown algae have received attention due to their numerous bioactive compounds and biological properties (Ismail et al., 2023), such as those from the genus *Sargassum* sp., which are abundant along the Brazilian coast (Melo et al., 2021; Yamashita et al., 2021). These algae dominate over other species in the environments where they occur, forming extensive and dense banks, covering from subtidal regions with sandy-rocky substrate to the lower limit of intertidal regions of both sheltered and exposed cliffs. These algae have significant commercial applicability as a source of alginate (Mafra & Cunha, 2010); however, in Brazil, despite the growing demand, there is no alginate production, and they are underutilized or even invisible.

In general, their nutritional composition can vary, as it is influenced by many factors related to species, cultivation location, exposure to light intensity, salinity, atmospheric conditions, harvesting period, and seasonal variations (Peñalver et al., 2020; Subbiah, Xie, et al., 2023). Seaweeds are a low-calorie food, with high nutritional value due to their vitamin, protein, and mineral content. In addition to containing vitamins A, B1, B12, and C, they are also natural sources of water-soluble and fat-soluble vitamins, such as thiamine, riboflavin, β-carotene, and tocopherols (Suresh Kumar et al., 2014).

The vast majority of commercially available seaweeds are in the dehydrated form, which stabilizes them and extends their shelf life since they have natural moisture between 60 to 90% (Milledge et al., 2016), making them perishable when removed from the sea because they have

an active biological system. They can be dried using various methods, such as sun drying, performed on racks by communities; in drying ovens with control of time, temperature, and airspeed, more commonly used industrially and for more specific purposes; and by freeze-drying, which preserves color and heat-sensitive nutrients. These processes can also interfere with their nutrient composition.

Studies indicate that the freeze dryer is one of the most effective approaches for producing high-quality dry products. This equipment removes water through the vacuum sublimation process at low temperatures and pressure, preserving phenolic compounds (Subbiah, Duan, et al., 2023; Wong & Cheung, 2001). However, it is important to highlight some disadvantages associated with the use of the freeze dryer, such as high energy consumption and production costs. Subbiah et al. (2023) demonstrated that samples of seaweed dried in a freeze dryer consistently exhibited high antioxidant potential (37.15 AAE mg/g), compared to oven drying (21.97 AAE mg/g) and vacuum drying (2.23 AAE mg/g).

In this context, the objective of this study was to characterize the brown seaweed *Sargassum* sp. from the coast of São Paulo, Brazil, regarding its nutritional and techno-functional properties using two drying methods.

2 MATERIALS AND METHODS

2.1 Algae collection

Samples of the seaweed species *Sargassum* sp. were collected at Praia das Cigarras, located at the northern end of the São Sebastião, São Paulo, Brazil (Figure 1), with coordinates 45º 23’W; 23º43’S, between the summer of 2021 and the summer of 2022.

Figure 1. The map shows the geographic location of the seaweed sample collection site in São Sebastião, São Paulo, Brazil; A) *Sargassum* sp. bank in its rocky habitat before collection; and (B) after collection. The black point on the maps indicates the sampling location.

After collection, the seaweeds were transported in thermal boxes with ice to the laboratory. Before the drying process, the seaweeds underwent a cleaning procedure, which involved successive washings in fresh water to remove epiphytes and epifauna. Subsequently, the fronds of Sargassum sp. were divided into two batches. One batch was subjected to oven drying (SD) with air circulation and renewal (Tecnal, model TE - 394/2, Brazil), using a stainless steel rack. This process occurred at a temperature of 40°C, aiming to reach a moisture content below 10%. The second batch was frozen in an ultra-fast freezer (-30°C for 40 minutes) and then lyophilized in a benchtop freeze dryer (Liotop, model L108, Brazil) for 48 hours, until reaching a moisture content below 6% (SL).

The commercial seaweed (SC) was purchased from a supplier in China for comparison with the samples collected in Brazil.

The dried seaweeds, lyophilized seaweeds, and commercial seaweed were separately ground (to a particle size of less than 0.250 mm) in a commercial blender (Hamilton Beach, model HBH450, United States), packed in polyethylene bags (primary packaging), and multi-layer bags with one layer of aluminum (secondary packaging). The samples were kept at room temperature until their use.

2.2 Nutritional Characteristics

2.2.1 Proximate Composition

The freshly collected seaweed was evaluated for its moisture content to estimate its yield. The proximate composition of seaweeds dried in the oven (SD), lyophilized (SL), and commercial (SC) was determined according to the official methods of AOAC (2005) for moisture (method no. 925-09), ash (method no. 923-03), total protein was determined by the Kjeldahl method (method no. 920-87) and calculated using a nitrogen conversion factor of 6.25, which was used in studies on algae cited in Ortiz et al. (2006), Yaich et al. (2011) and Peinado et al. (2014). The total lipid content was determined according to Bligh & Dyer (1959).

Total dietary fiber was evaluated by the enzymatic-gravimetric method, using the Megazyme K-TDFR Kit (Megazyme International, Wicklow, Ireland), based on method no. 985.29 (AOAC, 2005), as described in the Kit protocol.

Total carbohydrates were calculated in % by difference using the equation: Carbohydrates = 100 – (lipids + proteins + ash). All results were expressed in g/100g, dry basis.

2.2.2 Mineral Determination

The concentration of minerals, including macroelements (Na, K, Ca, and Mg) and trace elements (Fe, Mn, Cu, Zn), was determined using a flame atomic absorption spectrometer (FAAS) (Perkin Elmer, USA, model AAnalyst-200), according to the procedure described by Silva et al. (2017).

2.2.3 Amino Acid Determination

The quantification of amino acid levels was carried out by high-performance liquid chromatography (HPLC), according to the methodology described by White et al. (1986) and Hagen et al. (1989), determining 9 essential amino acids (phenylalanine, histidine, leucine, isoleucine, lysine, methionine, threonine, valine, and tryptophan) and 11 non-essential amino acids (aspartic acid, glutamic acid, alanine, arginine, cysteine, glycine, proline, serine, taurine, tyrosine, and hydroxyproline). Tryptophan was quantified through alkaline hydrolysis with LiOH 4N according to the method described by Lucas & Sotelo (1980).

2.2.4 Antioxidant Capacity

The antioxidant capacity is due to different types of compounds that differ in action mechanisms and can interact synergistically. For this reason, it is desirable to use more than one method to determine antioxidant capacity. In this study, the DPPH, ABTS, and FRAP in vitro methods were used. For the preparation of extracts, 1 mg of each seaweed flour was solubilized with methanol to obtain a sample of 1 mg of seaweed/1 mL of methanol.

a) DPPH Method

The radical scavenging capacity was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical as described by Mar et al. (2020) with slight modifications. The sample (10 µL) was added to 190 µL of DPPH methanolic solution (100 µM) and incubated in the dark for 30 min. Absorbances were then read on a microplate reader at 515 nm (Epoch 2, Agilent BioTek, Santa Clara, CA, USA), and a standard curve was prepared with Trolox ranging from 100 to 2000 µM ($y = -0.0004x + 0.7353$, $R2 = 0.9965$).

b) ABTS Method

For the 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assay, the protocol of Re et al. (1999) was followed with slight modifications. The sample was added to the ABTS solution at a ratio of 1:10 (v/v) and incubated in the dark for 6 min. Absorbances were then read on a microplate reader at 725 nm (Epoch 2, Agilent BioTek, Santa Clara, CA,

USA). A Trolox standard curve was prepared ranging from 125 to 2000 µM (y = -0.0003x + 0.7344, R2 = 0.9997).

c) FRAP Method

The Ferric Reduction Antioxidant Power (FRAP) assay was performed using the method previously described by Pulido et al. (2000). The FRAP reagent was prepared by adding acetate buffer (0.3 mol L-1, pH = 3.6), TPTZ solution (10 mM), and FeCl3.6H2O (20 mM) in a ratio of 10:1:1. In a microplate, an aliquot of 9 µL of the sample was mixed with 27 µL of ultrapure water and added to 270 µL of the FRAP reagent. The microplate was incubated for 30 min at 37°C, and absorbance was measured at 595 nm using a microplate reader at 725 nm (Epoch 2, Agilent BioTek, Santa Clara, CA, USA). Results were obtained by regression equation from the curve obtained from the standard ferrous sulfate solution of 250 to 2000 µM (y = 0.0009x - 0.1664, R2 = 0.9900) and expressed in µM Fe(II)/g of extract.

2.2.5 Total Phenolic Content

The total phenolic content of seaweeds was determined using a modified Folin-Ciocalteu method (Velioglu et al., 1998). The seaweed flour was added to the reaction mixture (1:1) of Folin-Ciocalteu reagent and sodium bicarbonate (6%). The mixture was kept in the dark at rest for 90 min and then analyzed on a microplate reader (Epoch 2, Biotek) at 750 nm. A gallic acid standard curve was made from 31.2 to 1000 µg/mL (y = 0.0029x + 0.2373, R2 = 0.9938), and the results were expressed in mg of gallic acid equivalents per gram (mg GAE/g) of seaweed flour.

2.3 Physicochemical Characteristics

2.3.1 Color Determination

The colorimetric parameters of seaweed in fresh state and in the form of flour, after drying and lyophilization, with commercial seaweed made only in flour form, were determined using the HunterLab UltraScan PRO colorimeter (Hunter Associate Laboratory Inc., Reston, USA), previously calibrated using white and black porcelain tiles. Measurements were taken under illuminant D65, with an observation angle of 10°. The CIELab color system (*L**, *a**, and *b**) was employed, and the results presented represent the average of five readings.

Color analysis was also determined through computerized images, adapting the protocol of Ayustaningwarno et al. (2021). Images of seaweed flours were captured using a 24.2 MP color digital camera (Sony α6000 with 16-50 mm lens, f/3.5-5.6, at 50 mm), mounted 25 cm

from the samples, set at ISO-100, with aperture f/6.3, and an exposure time of 1/80s. Color calibration, white balance adjustment, and background removal were performed in Adobe Photoshop 2020, and the resulting images were saved in TIFF format. The saved images were then processed using ImageJ software, supplemented by the Color Inspector 3D plugin. The region of interest was delineated with the Color Threshold tool. Color Inspector 3D subsequently generated a table detailing the colors detected in the red, green, and blue (RGB) spectrum and their respective percentages based on pixel distribution.

2.3.2 pH

The pH was determined using a benchtop pH meter (HI 2221-02, Hanna Instruments, USA), following the methodology proposed by Mutlu et al. (2018), with adaptations. For the analysis, 1g of seaweed was weighed in 50 mL Falcon tubes, followed by the addition of 10 mL of distilled water. Subsequently, the tubes were subjected to shaking for a period of 30 minutes. After this procedure, they were centrifuged for 6 minutes at 3000 rpm, and the pH was then measured in the resulting supernatant.

2.3.3 Scanning Electron Microscopy (SEM)

Image analysis was performed on a scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS) detector (Leo 440i, EDS 6070, SEM/EDS: LEO Electron Microscopy/Oxford, Cambridge, England). Samples of seaweeds (SD, SL, and SC) were spread on slides and then fixed on a sample holder with double-sided carbon adhesive tape, metallized with a thin layer of gold using a sputter coater (Emitech, K 450, Kent, UK). Analyses were performed at an acceleration voltage of 20 kV and beam current of 50 pA to obtain micrographs. A large number of micrographs were captured to select the most representative ones.

2.3.4 X-ray Diffraction (XRD)

X-ray diffraction data of seaweed flour (SD, SL, and SC) were collected using an Empyrean diffractometer from Panalytical (Netherlands) in reflection mode, employing CuKα radiation (λ = 1.54056 Å). The equipment operated with an acceleration voltage of 40 kV and a current of 40 mA. The diffractometer was configured with a HD Bragg-Brentano mirror, a 0.02 rad Soller slit, a 1-degree anti-scatter slit, and a 1/4 degree divergence slit in the incident beam. To obtain the diffracted beam, a 0.04 rad Soller slit and a 9 mm anti-scatter slit were

employed. Detection of X-ray photons was performed through an area detector (PIXcel3D-Medipix3, 1x1 detector). Mylar sample holders were used, without background incorporation.

2.3.5 Differential Scanning Calorimetry (DSC)

Thermal properties were determined using a DSC (Mettler Toledo, DSC1, Schwerzenbach, Switzerland). 2.5 mg of seaweed sample (SD, SL, and SC) were collected using a metal microspatula, and about 7.5 g of distilled water were weighed into Al crucibles (40 µL). The crucibles were sealed with a lid and individually taken to the equipment for analysis. The samples were heated from 35 to 120 °C at a heating rate of 10 °C/min under an inert N2 atmosphere at a flow rate of 80 mL/min.

2.3.6 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR was performed on an infrared spectrometer (IRPrestige-2, Shimadzu, Kyoto, Japan), dispersing the material in potassium bromide (KBr) pellets, where a ratio of 1:100 (sample:KBr) was employed using 2 mg of seaweed sample (SD, SL, and SC):200 mg spectroscopic grade KBr. Readings were taken in the range of 4000 to 400 cm-1 with a resolution of 4 cm-1, with 24 scans. The spectra were analyzed with IRSolution software, version 1.60.

2.4 Techno-functional Characteristics

The techno-functional characteristics were assessed for commercial seaweed, both dried and lyophilized, where all sample masses were measured on a dry basis.

2.4.1 Water Solubility Index (WSI) and Water Absorption Index (WAI)

WSI and WAI were determined following the method of Anderson (1982), with slight modifications. For the analysis, 0.80 g of sample was weighed and placed in 50 mL Falcon tubes. Subsequently, 10 mL of distilled water was added to the tubes, followed by agitation for 30 minutes. The tubes were then centrifuged at 3000 rpm for 10 minutes. The resulting supernatant was weighed, adjusted to 10.8 mL, transferred to an aluminum plate, and dried in a circulating air oven at 105°C until reaching a constant mass. The indices were calculated using equations 1 and 2, with WSI corrected for the total volume.

$$\text{WSI}\ (\%) = \frac{\text{weight of evaporation residue (g)}}{\text{dry sample weight (g)}} * 100 \quad (1)$$

(2)

$$\text{IAA} = \frac{\text{weight of the centrifugation residue (g)}}{\text{dry sample weight (g)}}$$

2.4.2 Oil Holding Capacity (OHC)

To determine the OHC (g oil/g sample), the method proposed by Kumar et al. (2014) was followed with adaptations. For the analysis, 0.50 g of the sample was weighed in a 50 mL Falcon tube, and 5.0 mL of soybean oil at 25°C was added. The mixture was intermittently homogenized and then subjected to centrifugation at 2200 rpm for 15 minutes. Immediately after centrifugation, the supernatant was carefully removed by inverting the tubes for 2 minutes, which were then weighed. The calculation of the absorbed oil per 1.0000 g of sample was performed as indicated by equation 3.

$$\text{OHC}\left(\text{g}\frac{\text{oil}}{\text{g}}\text{sample}\right) = \frac{\text{oil absorbed by the sample(g)}}{\text{dry sample weight (g)}} \quad (3)$$

2.4.3 Foam Capacity and Stability (FC)

The method by Okezie and Bello (1988), with modifications, was used to determine foam capacity and stability. A solution of 50 mL of distilled water and 1.500 g of sample was prepared, transferred to a graduated cylinder, allowed to stand for 15 minutes, and the initial volume was measured. Subsequently, it was agitated with a mixer for 2 minutes. The height of the foam formed and its stability were checked by recording the foam volume every 5 minutes for 30 minutes. The volume increase is expressed as a percentage of the foam formation capacity, as per equation 4. For foam stability, the FC equation was used as a reference, but with the volume after agitation at each analyzed time.

$$\text{Foaming capacity (\%)} = \frac{\text{volume after agitation} - \text{volume before agitation}}{\text{volume before agitation}} \text{x } 100 \quad (4)$$

2.4.4 Emulsion Capacity (EC) and Emulsion Stability (ES)

The analyses of EC and ES were conducted according to the protocol established by Stone et al. (2019) with adjustments. In a 50 mL Falcon tube, 1.5 g of algae flour was suspended in 15 mL of water and 15 mL of soybean oil. The suspension was homogenized at 10,000 rpm for 1 minute, and the height of the emulsion was measured with a ruler. Then, the emulsion was centrifuged at 1300 rcf for 5 minutes, resulting in the formation of three distinct layers: serum (bottom), emulsion (middle), and oil (top). The EC was calculated using Equation 5.

$$EC = \frac{\text{emulsion layer after centrifugation (cm)}}{\text{initial emulsion height (cm)}} \times 100 \quad (5)$$

For ES, the emulsion was prepared as done for EC and then heated in a water bath (80°C) for 30 minutes and cooled in running water for an additional 30 minutes. The emulsion was centrifuged as described earlier. ES was calculated by dividing the EC of the emulsion after heating by the EC of the initial emulsion and the results expressed as a percentage.

2.5 Statistical Analysis

The results of the analyses were expressed as mean ± standard deviation, and the data were subjected to analysis of variance (ANOVA) with a significance level set at 5%. When analysis of variance revealed significance, the Scott-Knott test was employed for the determination of statistical differences between the means ($p < 0.05$), using the SISVAR software version 5.6 (UFLA, Lavras MG, Brazil).

3 RESULTS AND DISCUSSION

Table 1 presents the physicochemical composition of the seaweed flours (Table 1).

Table 1. Comparison of proximate composition (dry basis[1]), pH, and mineral content between seaweeds dried in an oven (SD), lyophilized (SL), and commercial (SC)

Analysis	Seaweed		
	SD	SL	SC
Moisture (%)[2]	$11.66^{b} \pm 0.37$	$11.06^{c} \pm 0.16$	$12.78^{a} \pm 0.17$
pH	$4.93^{c} \pm 0.34$	$6.04^{b} \pm 0.14$	$7.20^{a} \pm 0.49$
Proximate composition (g/100g)			
Protein	$15.47^{b} \pm 0.48$	$16.81^{a} \pm 0.28$	$13.65^{c} \pm 0.54$
Lipids	$3.32^{b} \pm 0.25$	$3.98^{a} \pm 0.27$	$2.38^{c} \pm 0.08$
Ash	$17.60^{b} \pm 0.16$	$13.04^{c} \pm 0.07$	$19.05^{a} \pm 0.31$
Total carbohydrates	$63.59^{c} \pm 0.54$	$66.15^{a} \pm 0.43$	$64.90^{b} \pm 0.43$
Minerals (mg/100g of sample)			
Sodium	$290.80^{c} \pm 6.43$	$379.81^{a} \pm 7.28$	$335.25^{b} \pm 4.42$
Potassium	$2918.23^{a} \pm 9.95$	$1557.77^{b} \pm 7.97$	$769.07^{c} \pm 2.66$
Calcium	$2582.34^{b} \pm 8.31$	$2638.63^{b} \pm 9.75$	$5181.66^{a} \pm 6.75$
Magnesium	$791.58^{b} \pm 4.50$	$919.53^{a} \pm 4.55$	$687.39^{c} \pm 4.05$
Iron	$36.95^{c} \pm 0.14$	$93.60^{a} \pm 1.16$	$49.32^{b} \pm 0.55$
Manganese	$9.09^{a} \pm 0.13$	$7.34^{b} \pm 0.01$	$6.53^{c} \pm 0.08$
Copper	$0.37^{b} \pm 0.04$	$0.30^{c} \pm 0.00$	$0.64^{a} \pm 0.00$
Zinc	$2.51^{a} \pm 0.01$	$2.33^{b} \pm 0.01$	$1.73^{c} \pm 0.01$

[1]Data transformed on a dry basis for comparison and discussion of the results. Results are presented as mean ± standard deviation. Means followed by different letters in the same row differ significantly from each other by Scott-Knott multiple comparisons test ($p<0.05$). [2]Moisture content of seaweed flour after processing and drying.

The flours (SD, SL, and SC) showed significant differences in composition, with SL showing the highest levels of protein, lipids, and carbohydrates. Regarding proteins, an average of 15.31g/100g was found, a value similar to that found in some cereals and legumes. The protein content of brown algae can vary from 3 to 20.5% (Fauziee et al., 2021); however, with advances in knowledge, these values can be optimized. For example, planning the harvest, as it is known that the highest protein levels are found at the end of winter (Černá, 2011).

Marine algae contain considerably higher concentrations of all necessary minerals than any other terrestrial vegetation (Kasimala et al., 2020), which is represented in Table 1 by their ash content, which ranged from 13 to 19%. The predominant minerals were calcium, potassium, magnesium, and sodium, followed by iron, manganese, and zinc. Studies on their bioavailability and whether they meet daily human consumption needs could be beneficial to provide alternatives for people with special diets that restrict foods that are sources of these minerals.

The figure 2 shows that the dietary fiber content of the seaweed flours is above 70%, indicating that it is a fiber-rich food. Generally, seaweeds are characterized by their high fiber content (Venugoapl, 2011; Afonso et al., 2019). Wong and Cheung (2001), analyzing Sargassum *hemiphyllum*, found dietary fiber values ranging from 49.5 to 61.1% on a dry basis. Similar values were found by Cofrades et al. (2008), who characterized the brown algae *Himanthalia elongata* and obtained 50.31% dietary fiber in dry mass.

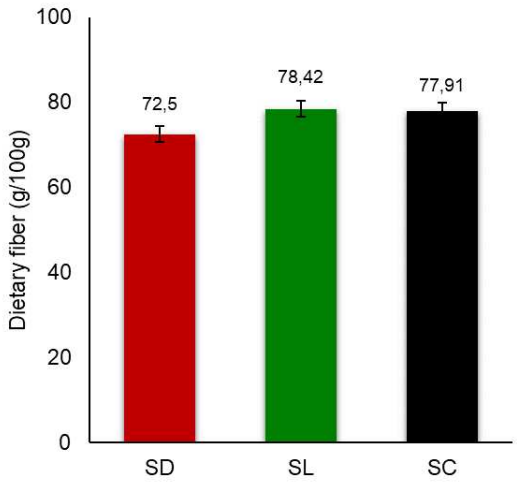


Figure 2. Dietary fiber content, on a dry basis, present in the flours of seaweeds dried in an oven (SD), lyophilized (SL), and commercial (SC).

The results of our study are above the values reported in these studies, which may be related to the method employed for analysis. The enzymatic-gravimetric method is sensitive and may have detected specific types of dietary fibers that may not have been fully identified in previous studies. Additionally, environmental conditions such as temperature, water salinity, available nutrients, and exposure to sunlight can influence the chemical composition of algae (Vieira et al., 2018). The harvest season also influences the dietary fiber content; when harvested during active growth, it can positively impact dietary fiber levels.

The amino acid composition of the algae according to different drying methods is presented in Table 2.

Table 2. Amino acid content of seaweeds dried in oven (SD), lyophilized (SL), and commercial (SC).

Amino acid	Seaweed					
	SD		SL		SC	
Essential	g/100g	mg/g protein	g/100g	mg/g protein	g/100g	mg/g protein
Histidine	0.17	10.99	0.20	11.90	0.17	10.11
Isoleucine	0.43	27.80	0.50	29.74	0.49	29.15
Leucine	0.79	51.07	0.93	55.32	0.91	54.13
Lysine	0.56	36.20	0.62	36.88	0.46	27.36
Methionine	0.27	17.45	0.30	17.85	0.29	17.25
Phenylalanine	0.53	34.26	0.61	36.29	0.60	35.69
Threonine	0.50	32.32	0.57	33.91	0.52	30.93
Valine	0.54	34.91	0.61	36.29	0.61	36.29
Tryptophan	0.07	4.52	0.06	3.57	0.04	2.38
EAA (%)[1]	40.67		43.39		43.84	
Non-essential						
Aspartic acid	0.88	56.88	0.81	48.19	0.64	38.07
Glutamic acid	1.37	88.56	1.18	70.20	0.96	57.11
Alanine	0.79	51.07	0.83	49.38	0.78	46.40
Arginine	0.52	33.61	0.59	35.10	0.57	33.91
Cystine	0.06	3.88	0.07	4.16	0.09	5.35
Glycine	0.61	39.43	0.67	39.86	0.68	40.45
Proline	0.44	28.44	0.50	29.74	0.52	30.93
Serine	0.54	34.91	0.64	38.07	0.56	33.31
Tyrosine	0.36	23.27	0.40	23.80	0.39	23.20
Taurine	0.03	1.94	0.02	1.19	0.02	1.19
Hydroxyproline	0.03	1.94	0.03	1.78	0.03	1.78
NAA (%)[2]	59.33		56.61		56.16	
Soma dos TAA[3]	9.49		10.14		9.33	

[1]EAA = essential amino acids. [2]NAA = non-essential amino acids. [3]TAA = total amino acids.

The amino acid requirements vary from person to person based on age, sex, body weight, daily activity, and physiological states (Raja et al., 2022). Overall, the algae exhibited similar amino acid profiles, with the presence of all essential amino acids in values above or very close to those recommended by FAO for the adult population above 18 years old (Supplementary Material 1), with the highest levels of aromatic amino acids (Phenylalanine + Tyrosine) followed by leucine and lysine.

Due to the presence of lysine, algae can be used to balance the amino acid composition in cereal-based products, which often have a low lysine content. All samples showed similar profiles of non-essential amino acids. Glutamic and aspartic acids were the most abundant amino acids (Table 2), consistent with the findings of Mišurcová et al. (2014) and Vieira et al. (2018), who also analyzed brown algae. The high levels of the acidic amino acids glutamic and aspartic acids may explain the characteristic taste of algae and seafood products, contributing to the sensation of "umami" (Raja et al., 2022), making them a good candidate to replace sodium glutamate in food preparations, making them free of flavor additives.

Table 3 presents the total phenolic content and antioxidant potential of the algae dried by different methods. There was a significant difference among all samples, with SL flours showing the highest levels of both antioxidants and bioactive compounds, although all seaweed flours can be a good source of phenolic compounds.

Table 3. Antioxidant capacity and total phenolics of seaweed flours dried in an oven (SD), lyophilized (SL), and commercial (SC).

Analysis	Seaweed		
	SD	SL	SC
Antioxidant capacity (µmol TE/g dry basis)			
DPPH	$470.58^{b} \pm 6.29$	$578.08^{a} \pm 6.29$	$172.25^{c} \pm 5.00$
ABTS	$831.66^{b} \pm 1.67$	$1001.66^{a} \pm 1.67$	$295.55^{c} \pm 10.72$
FRAP	$390.81^{b} \pm 2.80$	$435.63^{a} \pm 2.80$	$346.00^{c} \pm 3.33$
Bioactive compounds (mg GAE/g dry basis)			
Total phenolic content (TPC)	$126.56^{b} \pm 1.44$	$144.49^{a} \pm 0.87$	nd

The results are presented as mean ± standard deviation. Means followed by different letters in the same row differ significantly from each other by Scott-Knott multiple comparisons test ($p<0.05$). For TPC, a t-test was used. "nd" stands for not detected.

Wong and Cheung (2001) analyzed three species of Sargassum and concluded that lyophilization provided better nutritional quality and greater potential to act as a functional

ingredient. Subbiah et al. (2023) also demonstrated that samples of algae dried by lyophilizer consistently exhibited high phenolic and antioxidant potential, unlike those dried in a vacuum oven, indicating that if the goal is to consume algae as a source of antioxidants, this process is the most suitable for removing water without impairing these compounds.

The color of the seaweed flours was analyzed, and the results are presented in Table 4 and Figure 3, respectively. It can be observed that SL flour showed the highest L* values (41.84), indicating a lighter color compared to SD and SC. These findings can be related to the drying process, as lyophilization better preserves the original color of foods. The low temperature and reduced pressure in lyophilization minimize the degradation of natural pigments present in seaweeds, resulting in a more effective maintenance of color. Natural pigments such as chlorophyll and carotenoids can be preserved in greater quantity and quality during lyophilization, contributing to a more concentrated and vibrant color, as found in the SL sample.

Table 4. Color of seaweed flours dried in oven (SD), lyophilized (SL), and commercial (SC).

Analysis	Seaweed		
	SD	SL	SC
*L**	$29.87^{b} \pm 0.39$	$41.84^{a} \pm 0.38$	$28.00^{c} \pm 0.44$
*a**	$1.06^{b} \pm 0.21$	$1.18^{b} \pm 0.10$	$3.65^{a} \pm 0.24$
*b**	$9.47^{b} \pm 0.52$	$14.54^{a} \pm 0.44$	$9.33^{b} \pm 0.22$
Color in RGB system			

The results are presented as mean ± standard deviation. Means followed by different letters in the same row differ significantly from each other according to the Scott-Knott multiple comparisons test ($p < 0.05$).

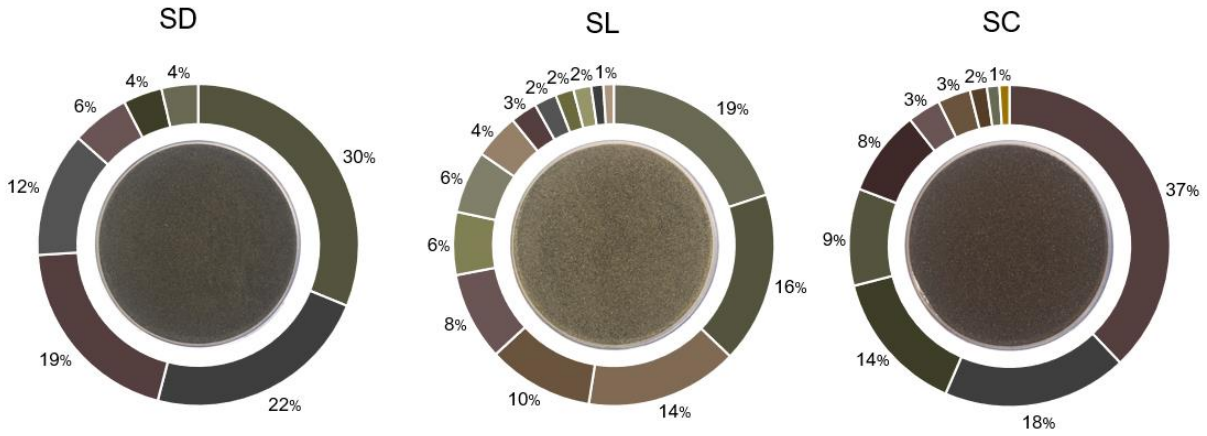


Figure 3. Frequency distribution of colors present in dried seaweed samples in oven-dried (SD), lyophilized (SL), and commercial (SC) forms.

Where: The central image is a real photograph of the flours.

In SD, due to exposure to higher temperatures, oxidation of pigments and Maillard reaction may have occurred, leading to the formation of darker colored products that could alter the color of the samples.

The color analysis conducted using ImageJ software provided a detailed and quantitative perspective of the colors present in the seaweeds (Figure 3). The seaweeds SD, SL, and SC exhibited 44, 75, and 59 distinct colors on their surface, respectively (Supplementary Material 2). In all seaweeds, the predominant color was brown, with various shades of brown. In SD, the predominant colors were dark brown and gray (~60%), SL was characterized by green tones (~60%) and light brown (~30%). When comparing the color distribution, it can be observed that lyophilization preserves the colors present in the sample. SC presented darker shades, ranging from green to reddish-brown, with the latter accounting for 37% of the colors.

The SEM analysis of SD and SL flours revealed details about the morphology of the samples, as visualized in Figure 4. Comparing SD and SL seaweeds, A2 with B2, it can be observed that SL (Figure 4 B2) exhibited better preservation of the original cellular structure, showing more intact cells, a more porous texture, and a more open and less collapsed surface, whereas SD structures appeared to be more compact and denser (Figure 4 A2). The commercial sample (SC) appears to have a more compact structure with the presence of agglomerations, which may be related to the drying method.

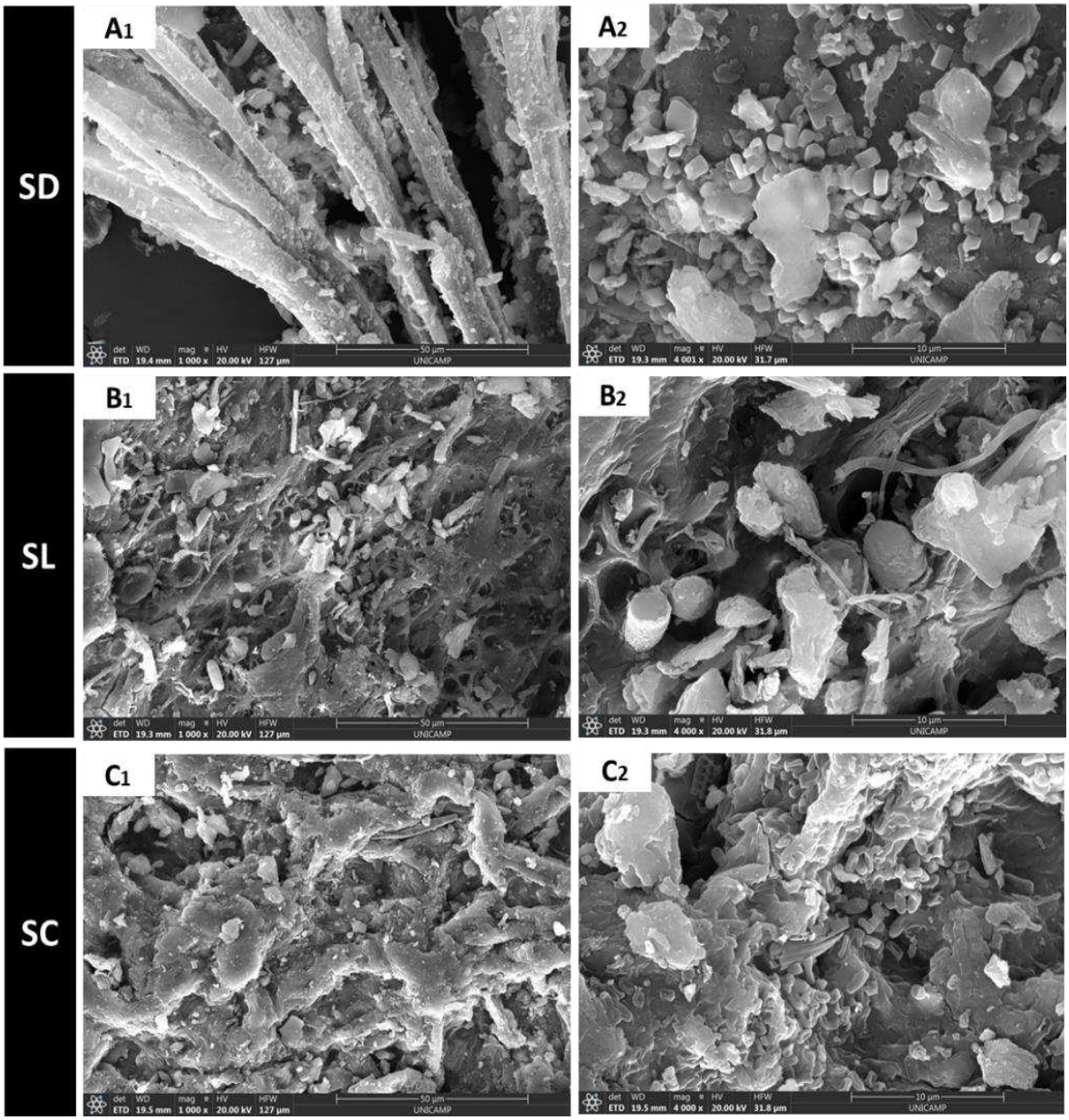


Figure 4. Scanning electron micrographs (SEM) of seaweed flours dried in an oven (SD), lyophilized (SL), and commercial (SC)

Where: A1 = SD flour with a magnification of 1000x; A2 = SD flour with a magnification of 4000x. B1 = SL flour with a magnification of 1000x; B2 = SL flour with a magnification of 4000x. C1 = SC flour with a magnification of 1000x; C2 = SC flour with a magnification of 4000x.

Figure 5 illustrates a comparison of X-ray diffraction patterns for seaweed flour samples SD, SL, and SC. In Figure 5(A), the three diffraction patterns are displayed with vertical shifts to facilitate comparisons. It is observed that the XRD patterns of all three samples exhibit both narrow and broad peaks. While the narrow peaks indicate the presence of crystalline structures,

the broad peaks may suggest the presence of semicrystals, nanocrystals, or amorphous structures. Furthermore, it is noted that the XRD pattern of sample SC displays a greater number of peaks compared to the other two, indicating a higher diversity of phases or crystalline components.

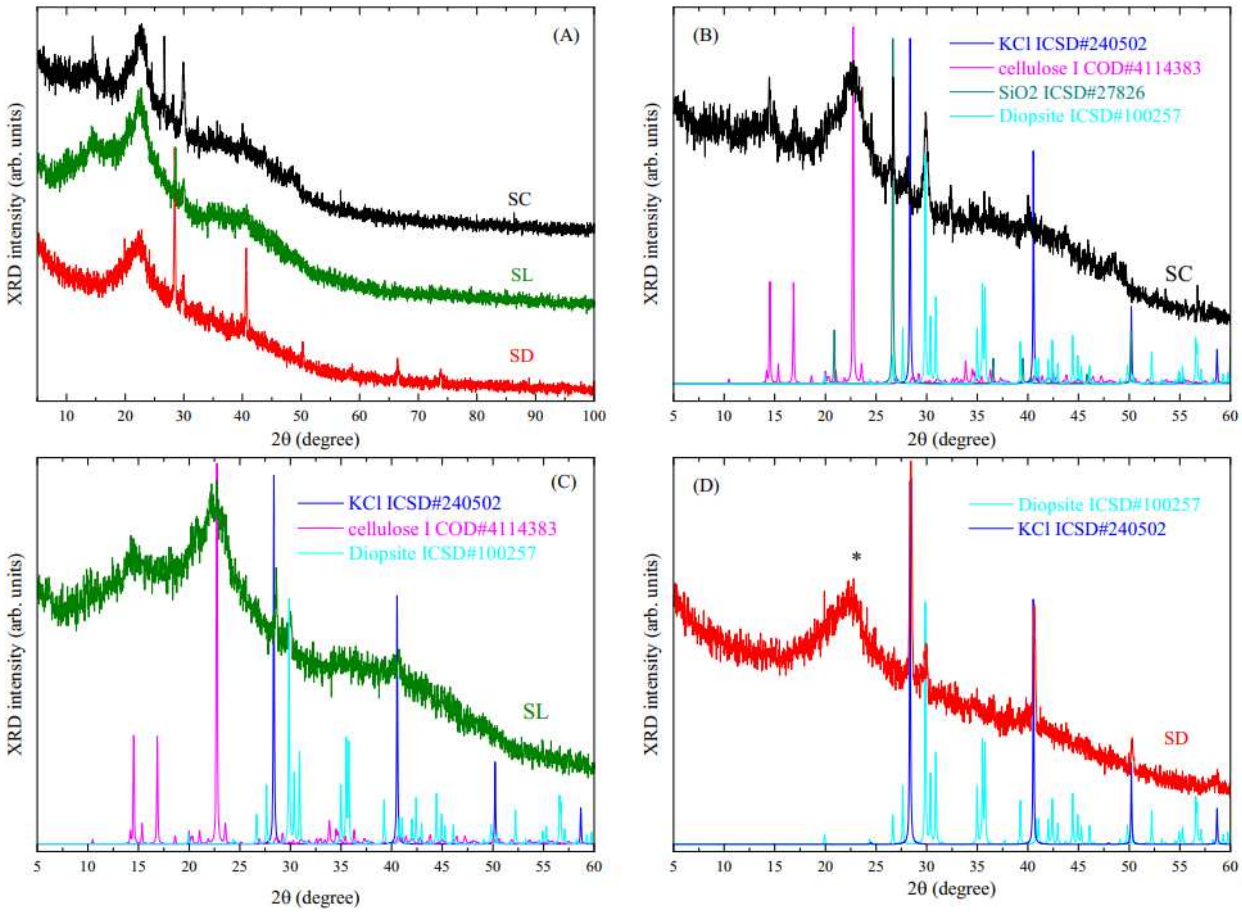


Figure 5. (A) X-ray diffraction patterns of seaweed flours dried in an oven (SD), lyophilized (SL), and commercial (SC); Phase identification of samples: (B) commercial, (C) lyophilized, and (D) oven-dried.

In Figures 5(B), (C), and (D), we illustrate the peak identification in the three diffraction patterns using XRD standards calculated with the Mercury program (MacRae et al., 2020) from the ICSD (Zagorac et al., 2019) and COD (Vaitkus et al., 2023) databases, which contain the crystallographic information.

As observed, all three patterns exhibit prominent peaks around 2θ = 28° and 40°, which closely correspond to potassium chloride (ICSD#240502) with cubic symmetry and Fm-3m

space group. The presence of KCl is notably discernible in the X-ray diffraction (XRD) patterns of the SD sample, contributing to peaks at 2θ = 50.5°, 58.5°, 67°, and 72.4° as well.

In Figure 5(B), it is evident that the SC sample contain quartz, as indicated by the peak observed at 2θ = 26.7°, consistent with SiO_2 (ICSD#27826), characterized by rhombohedral symmetry and space group *P 32 2 1*, which is not present in samples SL and SD.

Furthermore, a distinct peak at 2θ = 30° is evident in the XRD pattern of sample SC, which is also discernible in the other two XRD patterns albeit with reduced intensity. Considering the FAAS analysis, which revealed the results in Table I, indicating the presence of Na, Ca, Mg, and Fe, and following extensive research in crystallographic databases, we identified two plausible proposals: Augite (ICSD#75294) and Diopside (ICSD#100257). Both consist of compositions of Ca, Na, Mg, Fe, Si, and O, with a monoclinic symmetry structure and space group *C 2/c*. Their chemical formulas are $(Ca_{0.774}Na_{0.226})(Mg_{0.901}Fe_{0.099})Fe_{0.011}(Si_2O_6)$ and $(Mg_{0.964}Fe_{0.036})(Ca_{0.94}Na_{0.06})(Si_2O_6)$, respectively. Both minerals belong to the pyroxene group, common in igneous and metamorphic rocks from the algae collection region (Garda & Garda, 2001).

The broad peaks at around 2θ = 14.5°, 17° and 22.6°, in the SC and SL samples, correspond to cellulose semicrystals. Natural cellulose exists in two primary forms known as cellulose I, which comprises two allomorphs – cellulose I_α (triclinic symmetry) and cellulose I_β (monoclinic symmetry) (VanderHart & Atalla, 1984; Persson et al., 1991). Among these, cellulose I_α predominates in primitive organisms such as bacteria and algae, whereas cellulose I_β prevails in higher plants (Rongpipi et al., 2019; Thulluri et al., 2021). Consequently, the peaks observed at 2θ around 14.4°, 17.2°, and 22.6° in samples SC and SL in Figure 5 (B) and (C), respectively, were attributed to diffraction peaks of cellulose I_α (COD# 4114383) XRD patterns, that exhibits triclinic symmetry with space group *P1*. Conversely, Figure 5(D) demonstrates the lack of cellulose XRD peaks, substituted by a broadened diffuse peak centered at approximately 2θ = 22.5° in the SD sample. This suggests that the heat treatment used for drying induced amorphization of the cellulose I_α semicrystalline component.

In summary, X-ray diffraction (XRD) analysis reveals that the samples predominantly consist of cellulose, potassium chloride, and a mineral belonging to the pyroxene group, potentially derived from the substrate of the algae. The semicrystalline nature of cellulose is evident in both the SC and SL samples; however, the oven drying treatment applied to sample SD indicates cellulose amorphization. Moreover, the lyophilized sample exhibits a lower content of KCl compared to the oven-dried sample.

The Figure 6 presents typical DSC thermograms of seaweeds, where it can be observed that all samples did not exhibit observable endothermic peaks, being similar to each other. This may be related to the significant amount of dietary fibers and minerals, as shown in Table 1, whose thermal resistance may be higher than that used in the DSC, which was up to 130 °C.

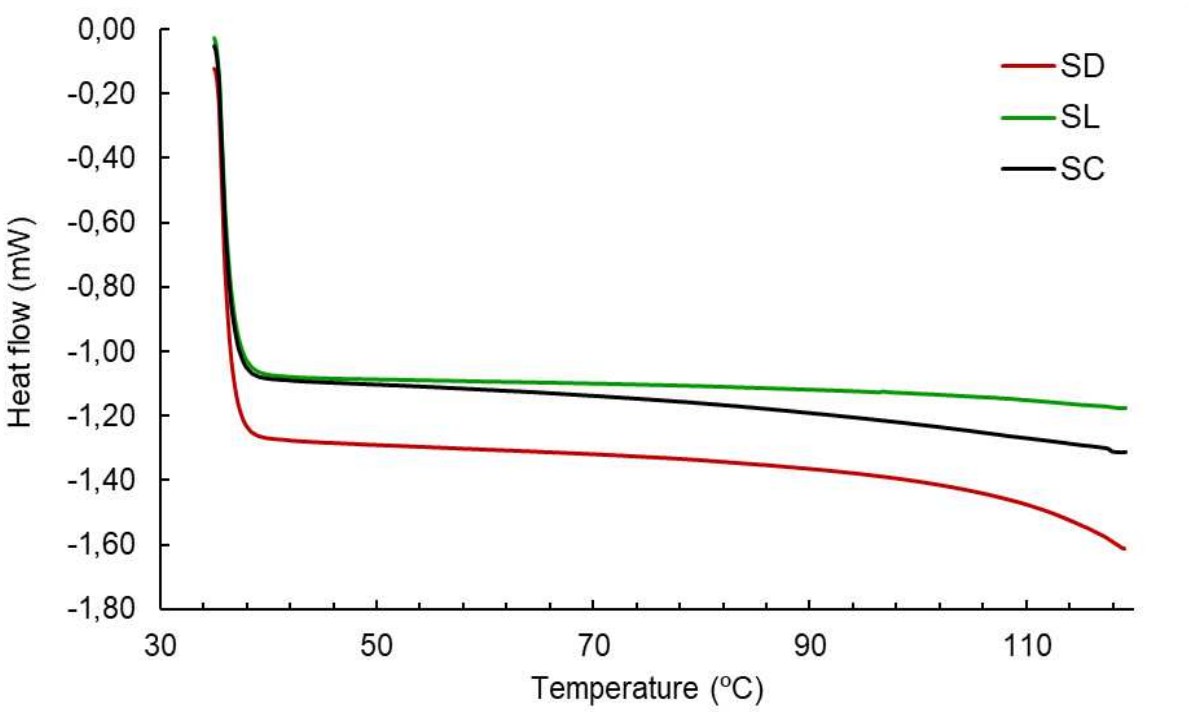


Figure 6. DSC thermograms of seaweed flours dried in an oven (SD), lyophilized (SL), and commercial (SC).

The FTIR spectra provide information about the structural composition of the components present in the seaweed flours. Figure 7 demonstrates that both SD, SL, and SC flours exhibited similar behavior, with bands in the same regions. The spectrum showed a band in the 800 cm^{-1} region, known as the angular deformation region, and a band in the 1050 cm^{-1} region, which can be associated with the stretching vibrations of primary amine bonds, due to the stretching of the C-N bond. Additionally, the presence of ethers and esters can lead to a band around 1050 cm^{-1} due to stretching vibrations of the C-O-C and C=O bonds, respectively. Bands in the 800 cm^{-1} and 1475 cm^{-1} regions may indicate the presence of aromatic groups, which is directly related to the presence of polyphenols, fucoxanthins, and carotenoids, characteristic of brown algae.

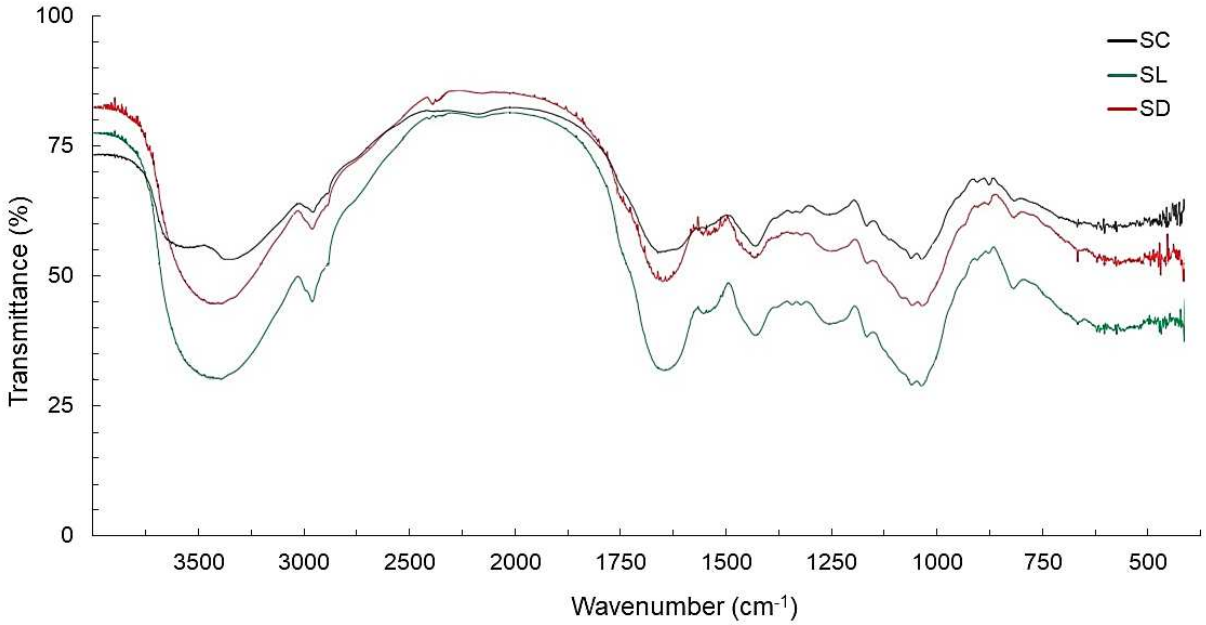


Figure 7. FTIR spectrum of seaweed flours dried in an oven (SD), lyophilized (SL), and commercial (SC).

The techno-functional properties of water absorption (WAI) and solubility (WSI), oil holding capacity (OHC), emulsion capacity (EC), and stability (ES) are presented in Table 5.

Table 5. Techno-functional properties of seaweed powders dried in an oven (SD), lyophilized (SL), and commercial (SC).

Analysis[1]		Seaweed		
	Abbreviation	SD	SL	SC
Water absorption index	WAI	$4.57^{c} \pm 0.86$	$7.52^{a} \pm 0.06$	$6.40^{b} \pm 0.16$
Water solubility index (%)	WSI	$19.74^{a} \pm 1.45$	$8.24^{b} \pm 0.09$	$7.78^{b} \pm 0.90$
Oil holding capacity (g/g)	OHC	$1.67^{a} \pm 0.34$	$2.48^{a} \pm 0.19$	$2.07^{a} \pm 0.57$
Emulsion capacity (%)	EC	$1.53^{c} \pm 0.01$	$37.54^{a} \pm 4.16$	$7.67^{b} \pm 1.66$
Emulsion stability (%)	ES	$1.46^{b} \pm 0.01$	$33.04^{a} \pm 6.03$	$1.49^{b} \pm 0.04$

[1]Results are presented as mean ± standard deviation of three replicates. Means followed by different letters on the same line differ significantly from each other according to the Scott-Knott test of multiple comparisons ($p < 0.05$).

Significant differences in WAI and WSI were found among the seaweeds, with SL flour exhibiting the highest absorption (7.52) and SD the highest solubility (19.74%). These differences are caused by the drying process; lyophilization results in flours with a more porous structure and larger surface area, providing more available sites for water absorption in SL flour, leading to a higher capacity for retaining liquids. On the other hand, oven drying may cause

modifications in the chemical structure and make water-soluble components more accessible, resulting in higher solubility of SD flour.

In this study, OHC did not show significant differences among the seaweeds, and the values found were similar to those reported by Fernández-Segovia et al. (2018) in different seaweed species. OHC is an important property from a technological point of view as it affects the texture of products, as demonstrated by Cofrades et al. (2008) who incorporated seaweed into meat emulsions and showed improvements in water and oil binding properties.

The emulsion capacity and stability were higher in SL (37.54%) than in SD (1.53%) and SC (7.67%). Oven drying may cause alterations in the molecular structure of the seaweed components, influencing their ability to interact and form emulsions. Lyophilization, being a gentler process, likely preserved the original characteristics and properties of the seaweed, including its ability to form emulsions.

Fleury and Lahaye (1991) reported that the physicochemical properties of seaweed flours reflect the characteristics of the fibers present, the conformation of proteins, and variations in the number and nature of water-binding sites in these molecules.

Comparative analysis of foam formation capacity and foam stability of seaweeds is presented in Figure 8.

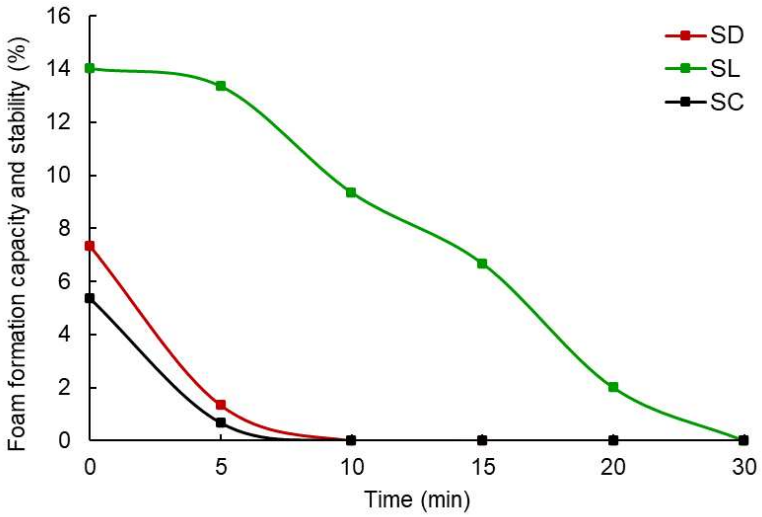


Figure 8. Foam formation capacity and stability of seaweed powders dried in an oven (SD), lyophilized (SL), and commercial (SC).

It can be observed that, similar to emulsion formation, both the capacity and stability of foam formation were higher in SL (14%). Lyophilization can preserve volatile gases released during foam formation, contributing to better gas retention in lyophilized samples. However,

foam stability was relatively low, as values were below 10% after 15 minutes, and with 30 minutes of rest, the analysis was concluded due to the absence of foam (0%).

Overall, the techno-functional properties add greater value to seaweeds in the food industry because, in addition to their nutritional properties, they can replace additives and/or other compounds that have been used to improve product properties.

4 CONCLUSION

The seaweed *Sargassum* sp. can be considered a source of nutrients, such as fibers, proteins, and minerals, with their contents varying depending on the drying methods used. The high fiber contents found indicate that incorporating this seaweed into low-fiber products may be a way to increase fiber intake and improve the nutritional value of these products. The amino acid profile suggests that seaweeds can be used to balance the amino acid composition in cereal-based products. The lyophilization drying process resulted in the best antioxidant properties and phenolic compounds. Overall, *Sargassum* sp. showed excellent solubility and emulsification properties, suggesting they could be used to formulate a wide variety of food products, such as sausages, bread, cakes, soups, and sauces. In addition to their technological and functional properties, seaweed cultivation and harvesting also offer employment opportunities for people living in coastal areas. Further research is needed to advance these results, provide data, and expand the entry of seaweeds into the food market, as seaweeds are predicted to be the food of the future.

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Supplementary material 1. Amino acid score of the seaweeds for adults (>18 years old)

Amino acids	Requeriment[1] (mg/g protein)	Amino acid content (mg/g protein)		
		SD	SL	SC
Histidine	15	10.99	11.90	10.11
Isoleucine	30	27.80	29.74	29.15
Leucine	59	51.07	55.32	54.13
Lysine	45	36.20	36.88	27.36
SAA[2]	22	21.33	22.01	22.60
AAA[3]	38	57.53	60.09	58.89
Threonine	23	32.32	33.91	30.93
Valine	39	34.91	36.29	36.29

[1] Scoring patterns for adults (> 18 years old) from the WHO/FAO/UNU (2007) report

[2] SAA = Sulphur amino acids (Methionine + Cystine)

[3] AAA = Aromatic amino acids (Phenylalanine + Tyrosine)

Supplementary material 2. Surface color distribution of oven-dried (SD), freeze-dried (SL) and commercial (SC) seaweed flours

Nº	Seaweed														
	SD					SL					SC				
	R	G	B	color	% frequency	R	G	B	color	% frequency	R	G	B	color	% frequency
1	84	84	62		29,94	106	106	84		18,747	84	62	62		36,761
2	62	62	62		21,97	84	84	62		16,197	62	62	62		18,025
3	84	62	62		19,159	128	106	84		14,455	62	62	40		14,069
4	84	84	84		12,08	106	84	62		10,005	84	84	62		9,459
5	106	84	84		5,588	106	84	84		8,345	62	40	40		8,35
6	62	62	40		3,762	128	128	84		5,952	106	84	84		3,241
7	106	106	84		3,534	128	128	106		5,902	106	84	62		3,2
8	106	84	62		0,746	150	128	106		4,298	84	62	40		1,659
9	62	40	40		0,737	84	62	62		2,529	106	106	84		1,215
10	40	40	40		0,519	84	84	84		2,124	128	106	84		0,974
11	128	106	84		0,5	106	106	62		1,727	84	84	84		0,763
12	128	128	106		0,339	150	150	106		1,69	40	40	40		0,571
13	128	106	106		0,283	62	62	62		1,139	62	40	62		0,292
14	62	84	62		0,162	172	150	128		0,983	150	128	106		0,249
15	106	106	106		0,123	62	62	40		0,758	128	106	106		0,214
16	150	128	106		0,081	150	150	128		0,713	128	128	106		0,185
17	62	40	62		0,073	128	106	106		0,676	106	62	62		0,145
18	84	62	84		0,057	150	128	84		0,6	128	84	84		0,078
19	84	62	40		0,046	172	172	128		0,585	172	150	128		0,067
20	150	150	128		0,045	172	150	106		0,533	150	150	128		0,04
21	84	106	84		0,044	84	62	40		0,305	150	106	84		0,036
22	40	62	40		0,032	194	172	128		0,258	84	40	40		0,032
23	128	128	84		0,032	128	106	62		0,187	150	128	128		0,03
24	150	128	128		0,025	194	194	150		0,165	150	128	84		0,028
25	172	150	128		0,022	194	172	150		0,129	40	40	18		0,027
26	150	150	106		0,014	216	194	150		0,103	128	128	84		0,027
27	106	106	62		0,01	172	172	150		0,078	128	84	62		0,025
28	128	128	128		0,008	128	84	84		0,077	172	128	106		0,022
29	172	172	128		0,008	150	128	128		0,073	172	150	106		0,022
30	40	62	62		0,007	84	84	40		0,055	106	106	106		0,022
31	128	84	84		0,006	62	40	40		0,054	194	172	150		0,015
32	172	172	150		0,006	106	106	106		0,05	106	106	62		0,014
33	194	172	150		0,005	172	128	106		0,041	150	106	106		0,014
34	40	40	18		0,004	84	106	84		0,038	172	172	150		0,012
35	40	40	62		0,004	62	84	62		0,038	150	150	106		0,012
36	62	84	84		0,004	216	194	172		0,033	194	172	128		0,011
37	150	128	84		0,003	128	84	62		0,032	84	62	84		0,01
38	106	128	106		0,003	216	216	172		0,028	172	172	128		0,008
39	62	62	84		0,002	106	128	84		0,028	128	106	62		0,008
40	172	150	106		0,002	194	194	128		0,027	62	40	18		0,006
41	194	172	128		0,002	150	106	84		0,026	194	150	128		0,005
42	216	194	172		0,001	238	216	172		0,022	194	194	150		0,005
43	194	194	150		0,001	40	40	40		0,021	62	84	62		0,005
44	194	194	172		0,001	128	150	106		0,016	84	40	62		0,005
45						172	172	106		0,013	194	194	172		0,004
46						194	194	172		0,012	128	128	128		0,004
47						106	128	106		0,011	172	150	150		0,003
48						84	106	62		0,011	40	18	18		0,003
49						194	150	128		0,01	40	62	40		0,003
50						216	194	128		0,009	216	194	150		0,003
51						128	128	128		0,008	216	194	172		0,003
52						216	216	150		0,006	172	128	128		0,002
53						150	172	128		0,006	106	62	40		0,002
54						150	106	106		0,005	84	84	40		0,001
55						150	150	84		0,005	84	106	84		0,001
56						106	62	62		0,005	172	128	84		0,001
57						238	216	194		0,004	194	150	106		0,001
58						128	150	128		0,004	216	172	150		0,001
59						216	172	128		0,003	216	216	172		0,001
60						216	172	150		0,003					
61						238	238	194		0,003					
62						194	172	106		0,003					
63						106	84	40		0,003					
64						40	62	40		0,003					
65						255	238	194		0,002					
66						238	216	150		0,002					

67	194	150	106		0,002
68	216	216	194		0,002
69	172	128	128		0,002
70	172	150	150		0,002
71	172	194	150		0,002
72	84	62	84		0,002
73	238	194	150		0,001
74	238	194	172		0,001
75	62	40	62		0,001

ARTIGO V (pesquisa)

Potencial uso da alga marinha *Sargassum* sp. em produtos extrusados à base de farinha de arroz

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POTENCIAL USO DA ALGA MARINHA S*argassum* sp. EM PRODUTOS EXTRUSADOS À BASE DE FARINHA DE ARROZ

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RESUMO: O estudo investiga o uso da alga marinha brasileira *Sargassum* sp. em produtos extrusados à base de farinha de arroz e avalia as propriedades tecno-funcionais e bioativas de farinhas de arroz extrusadas com algas marinhas secas em estufa e pelo processo de liofilização. Foram preparadas quatro formulação, sendo uma somente com farinha de arroz (R), uma com farinha de arroz e 1,5% de algas secas em estufa (R+SD), outra com farinha de arroz e 1,5% de algas secas por liofilização (R+SL) e a de farinha de arroz e 1,5% de algas comerciais (R+SC). As amostras foram submetidas a extrusão termoplástica, e os parâmetros de extrusão, cor, imagem, microscopia, propriedades tecno-funcionais (DSC, propriedades de pasta, IAA, ISA e CRO) e compostos bioativos (capacidade antioxidante por DPPH, ABTS, FRAP e fenóis totais) foram avaliados. A análises de cor mostrou que a amostra R+SL apresentou os maiores valores de L*(59,69), indicando uma coloração mais clara, enquanto R+SD mostrou coloração mais escura (L* 48,73) devido à oxidação dos pigmentos e reações durante a secagem em estufa. As imagens da microscopia eletrônica de varredura revelaram que a amostra R apresentou uma superfície mais homogênea e lisa, enquanto as amostras com algas mostraram rugosidades e heterogeneidade, associadas à presença de fibras das algas. A amostra R+SL apresentou o maior IAA (7,43) sugerindo que a liofilização melhora a capacidade de retenção de água. O ISA foi maior (24,95) na amostra R+SD, indicando que a secagem em estufa aumenta a solubilidade dos componentes da farinha. A CRO foi maior na amostra R (1,67), enquanto as amostras com adição de algas mostraram menores capacidades, sugerindo que as algas reduzem a capacidade de retenção de óleo da farinha de arroz. A capacidade de sequestro de radicais DPPH foi maior na amostra R+SL (147,25), indicando a preservação de compostos antioxidantes pela liofilização. Os resultados indicam o potencial das algas marinhas como ingredientes funcionais em produtos extrusados, contribuindo para o desenvolvimento de alimentos com benefícios à saúde. A escolha do método de secagem das algas é importante para otimizar as propriedades tecno-funcionais dos produtos finais.

PALAVRAS-CHAVE: Algas marrons; alimento funcional; extrusão termoplástica; análise cor; sustentabilidade.

1 INTRODUÇÃO

A crescente preocupação com a saúde e a busca por uma alimentação mais saudável tem impulsionado a investigação de novas fontes de nutrientes que possam promover benefícios à saúde humana (Wendin & Undeland, 2020). Nesse contexto, as algas marinhas surgem como uma alternativa promissora a partir das quais ingredientes altamente nutritivos e produtos alimentícios podem ser desenvolvidos. As algas marinhas são consideradas uma fonte de alimento pró-ambiental, pois não precisam de terra arável para crescer, seu cultivo não requer fertilizantes, pesticidas ou água doce, também são sequestradoras naturais de carbono e contribuem no aumento da biodiversidade dos ecossistemas onde são originadas e habitadas (Govaerts & Ottar Olsen, 2023; Sanjeewa et al., 2018).

O Brasil possui potencial para cultivar algas marinhas, principalmente porque o país possui 8.698 km de extensão de costa litorânea (IBGE, 2019) e condições de maritimidade favoráveis para o seu cultivo, no entanto, as atividades de cultivo são extremamente reduzidas e se concentram em apenas algumas localidades. Além disso, 18% da população brasileira ou seja, cerca de 37 milhões de habitantes, divididos em 279 municípios, vivem na faixa litorânea do Brasil (IBGE, 2022). Dentre as espécies encontradas no Brasil, a *Sargassum sp.* é abundante na costa brasileira.

O gênero *Sargassum* sp. é um grupo de algas marrons comestíveis, que são um componente importante das culinárias coreana, chinesa e japonesa (Sanjeewa et al., 2018). Além da fonte de alimento, estudos recentes mostraram que *Sargassum* sp. é fonte de compostos bioativos, principalmente fucoxantinas, floratanínos e fucoidanos, que têm ganhado considerável atenção devido aos seus comprovados benefícios à saúde (Cofrades et al., 2017).

As fucoxantinas são os carotenoides responsáveis pela cor específica das algas pardas (Gullón et al., 2020). Vários estudos demonstraram que esses pigmentos têm propriedades como agentes anticoagulantes (Dore et al., 2013), anticarcinogênicos (Ale et al., 2011), anti-inflamatórios (Hwang et al., 2015), antioxidantes (Chale-Dzul et al., 2017) e antimicrobianos (Huang et al., 2006). Além das propriedades culinários e benefícios a saúde, essas algas marinhas oferecem múltiplos usos e benefícios nos setores farmacêutico, ração animal, indústria cosmética e para agricultura (Sobuj et al., 2024).

Os pigmentos desempenham um papel fundamental na determinação das cores dos alimentos e sua principal aplicação é como corantes naturais (Ghosh et al., 2022). Nos últimos anos, devido à crescente preocupação dos consumidores com a saúde, tem havido uma tendência crescente no uso de pigmentos naturais, considerados ingredientes que promovem a

saúde, pois oferecem benefícios significativos e são vistos como alternativas promissoras aos corantes sintéticos (Salido et al., 2024). No entanto, os pigmentos, assim como a composição nutricional das algas marinhas variam de acordo com a época de colheita, espécie, localização geográfica e parâmetros de qualidade da água (MacArtain et al., 2007) e podem sofrer influência decorrente do pré-processamento que são submetidas.

Geralmente antes da sua utilização as algas marinhas passam pelo processo de secagem, que previne deterioração por microrganismos e reduz o custo de transporte (Neoh et al., 2016). A secagem pode ser realizada de forma natural (secagem ao sol), por meio de estufas de secagem com ou sem circulação de ar ou vácuo e liofilização. No entanto, a remoção de água durante a secagem do material vegetal é acompanhada por deformações que degradam a matriz vegetal e a funcionalidade de suas paredes celulares e membranas. A desintegração variável desta matriz resulta numa maior ou menor exposição dos compostos antioxidantes às reações de oxidação (Nguyen et al., 2016). A atividade antioxidante das algas marinhas pode ser afetada pela alta temperatura e pelo longo tempo de secagem (Neoh et al., 2016; Subbiah et al., 2023; Wong & Cheung, 2001). Estudos têm indicado que o liofilizador é um dos métodos mais eficazes para a produção de produtos secos de alta qualidade, pois remove a água por meio do processo de sublimação a vácuo em temperaturas baixas, preservando os compostos fenólicos e preservando os pigmentos do material (Uribe et al., 2019).

Para além das funcionalidades nutricionais e biológicas, os produtos à base de algas marinhas tornaram-se atrativos na indústria alimentícia, como demonstrado em uma revisão recente do nosso grupo de pesquisa (Tagliapietra & Clerici, 2023). A procura por alimentos prontos para consumo e saudáveis tem aumentado, e processos que podem ser versáteis e contribuir para inclusão de novos ingredientes têm sido explorados. Dentre as tecnologias de fabricação utilizadas atualmente destaca-se a extrusão termoplástica, que proporciona novos formatos e estruturas aos produtos, com diferentes características funcionais e nutricionais (Leonel et al., 2006; Salvador-Reyes et al., 2023).

Nesse sentido, estudos envolvendo ingredientes que possam melhorar o perfil nutricional e funcional de extrusados vem sendo desenvolvidos. Silva et al. (2021) utilizaram peptídeos bioativos de *Spirulina sp.* para obtenção de salgadinhos extrusados e demonstraram que com a adição de 2% de frações peptídicas houve aumento da eliminação do radical ABTS (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)). Jayakody et al. (2021) utilizaram algas marinhas *Ulva fasciata* para obtenção de snakcs e demonstraram que o *snack* apresentou

alto teor de minerais (13,91 g/100g), proteínas (19.18 g/100g) e fibras (44.64 g/100g) e agradou a população do sul da África.

As algas marinhas pertencentes ao gênero *Sargassum* são abundantes ao longo da costa brasileira, porém são ainda pouco exploradas em termos de pesquisa científica. Esta lacuna no conhecimento motiva o presente estudo. Até o momento, não foram identificadas pesquisas que investiguem a utilização de algas marinhas em produtos extrusados. Portanto, este estudo se propõe a ser um ponto de partida para explorar o potencial das algas marinhas na indústria de alimentos. O objetivo principal é avaliar o potencial do desenvolvimento de snacks à base de farinha de arroz com adição de algas marinhas secas, utilizando diferentes métodos de secagem, por meio do processo de extrusão termoplástica.

2. MATERIAL E MÉTODOS

2.1 Matérias-primas

As algas marinhas *Sargassum sp.* foram coletadas na Praia das Cigarras (45º 23'W; 23º43'S) localizada na extremidade norte do Canal de São Sebastião, São Paulo, Brasil (Figura 1).

Figura 1. O mapa mostra a localização geográfica do local de coleta de amostras de algas marinhas em São Sebastião (45º 23'W; 23º43'S), São Paulo, Brasil.

Após a coleta, as algas foram transportadas em caixas térmicas com gelo até o laboratório. Antes da secagem as algas foram higienizadas com sucessivas lavagens em água doce para separar quaisquer organismos exógenos a elas. Após a higienização, as frondes de *Sargassum* sp. foram divididas em dois lotes, sendo um seco em estufa com circulação e renovação de ar (Tecnal, modelo TE - 394/2, Brasil) usando varal de aço inox, a temperatura de 40ºC até atingir umidade inferior a 10%, e o outro lote liofilizadas em liofilizador de bancada (Liotop, modelo L108, Brasil) durante 12h até umidade inferior a 6%. As algas secas foram convertidas a pó (<0,250 mm), em blender comercial (Hamilton Beach, modelo HBH450, United States) acondicionadas em sacos de polietileno (embalagem primária) e sacos multicamadas com uma de alumínio (embalagem secundária), e mantidas em temperatura ambiente até a sua utilização. A alga marinha comercial (SC) foi importada de um fornecedor da China e a farinha de arroz (FA) foi fornecida pela SL Alimentos® (Mauá da Serra, Paraná, Brasil). Todas as matérias-primas foram padronizadas a 60 *mesh*.

A composição das algas marinhas secas em estufa (SD), liofilizadas (SL) e comercial (SC) foram determinadas em estudo anterior (artigo IV da tese). A farinha de arroz apresentou 10,86% de umidade, 8,6% de proteína, 0,31% de cinza, 1,55% de lipídeos e 78,6% de carboidratos disponíveis.

2.3 Preparação dos extrusados

Os extrusados foram elaborados em extrusora dupla rosca ZSK 30 co-rotativa (Werner Pfleiderer Corporation, Ramsey, EUA) de 29 L/D (relação comprimento/diâmetro). As misturas compostas de farinha de arroz e algas marinhas (Tabela 1) foram pesadas em lotes de 1.5 kg, acondicionadas com água destilada usando uma batedeira planetária (Hypo, modelo HB 12, Brasil) para atingir 15% de umidade, onde foram armazenadas durante 24h a temperatura ambiente para assegurar um nível de hidratação uniforme nas misturas.

Tabela 1. Identificação e formulação dos extrusados com algas marinhas coletadas no Brasil e adquiridas no comércio.

Identificação	Composição da mistura			
	RF (%)	SD (%)	SL (%)	SC (%)
R	100.0	0	0	0
R+SD	98.5	1.5	0	0
R+SL	98.5	0	1.5	0
R+SC	98.5	0	0	1.5

Onde: RF = Farinha de arroz; SD = *Sargassum* seca em estufa; SL = *Sargassum* liofilizada; SC = *Sargassum* comercial; R: Extrusado de farinha de arroz; R+SD: extrusado de *Sargassum* seca

em estufa; R+SL: extrusado de *Sargassum* liofilizada; R+SC: extrusado de *Sargassum* comercial.

A taxa de alimentação da mistura foi mantida constante em 200 rpm durante todo o cozimento por extrusão, a velocidade da rosca foi de 160 rpm, a taxa de alimentação de água de 0,7 l/h e as temperaturas das zonas 1, 2, 3 e 4 da extrusora foram fixadas em 70, 90, 120 e 115ºC, respectivamente. A configuração da rosca utilizada está demonstrada na Figura 2, sendo que os parâmetros do processo foram baseados em testes preliminares. Uma matriz circular com dois orifícios com diâmetro de 4 mm foi adotada no experimento.

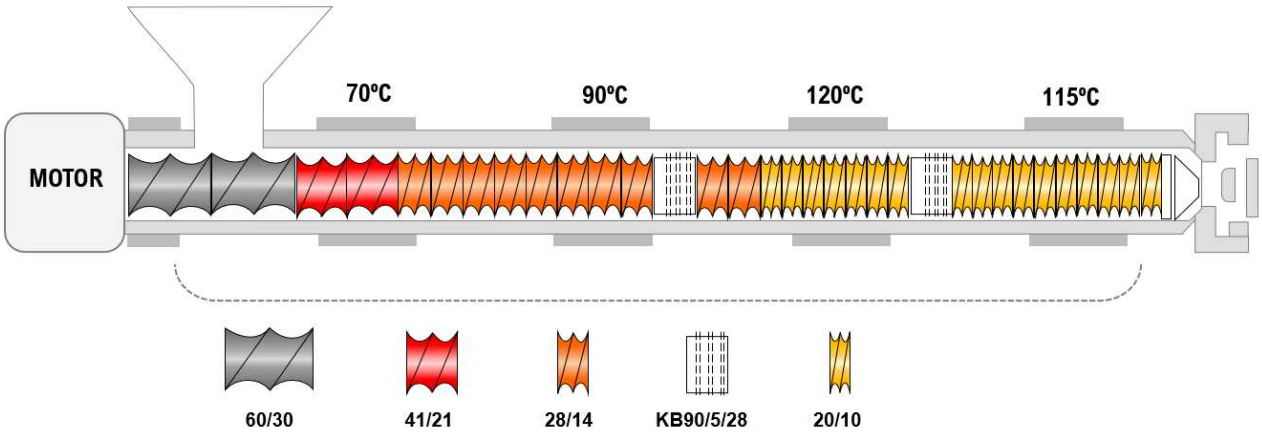

Figura 2. Representação esquemática da configuração da rosca e temperaturas utilizadas na extrusora dupla rosca para a produção dos extrusados.

Durante o processo de extrusão, o torque foi registrado para cada amostra e a energia mecânica específica (SME) foi calculada de acordo com Pansawat et al. (2008).

$$SME\ \left(W.\frac{h}{Kg}\right) = \frac{SS(rpm)\ x\ P(W)\ x\ T(\%)}{SSmax\ (rpm)\ x\ Q\left(\frac{Kg}{h}\right) x\ 100} \quad (1)$$

onde SME é a energia mecânica específica; SS, velocidade do parafuso (rpm); SS máx, velocidade máxima da rosca (500 rpm); P, a potência nominal da extrusora (9.000 W); T, torque médio registrado durante o tempo de amostragem (%); e Q, a vazão mássica (kg/h).

Os extrusados obtidos foram secos em estufa com circulação e renovação de ar (Tecnal, modelo TE - 394/2, Brasil) a 50ºC até umidade inferior a 5%. Em seguida, os produtos foram armazenados a 20°C em sacos metalizados lacrados, com proteção contra a luz e umidade até as análises posteriores.

2.4 Caracterização tecno-funcional dos extrusados

2.4.1 Cor dos extrusados

A análise de cor dos extrusados foi realizada por dois métodos. Primeiramente, foi realizada por meio de imagens computadorizadas, adaptando o protocolo detalhado por Ayustaningwarno et al. (2021), com modificações para adequação a produtos extrusados. Os snacks extrusados (12 peças de cada ensaio) foram posicionados sobre um fundo branco sob uma caixa de luz de 5400 K. As imagens foram capturadas usando uma câmera digital colorida de 24,2 MP (Sony α6000 com lente 16-50 mm, f/3.5-5.6, a 50 mm), montada a 25 cm das amostras, ajustada em ISO-100, com abertura f/6.3., e um tempo de exposição de 1/80s. A calibração de cores, o ajuste do balanço de branco e a remoção do fundo foram realizados no Adobe Photoshop 2020, e as imagens resultantes foram salvas no formato TIFF. As imagens salvas foram então processadas utilizando o software ImageJ, complementado pelo plugin Color Inspector 3D. A região de interesse foi delineada com a ferramenta Color Threshold. O Color Inspector 3D gerou posteriormente uma tabela detalhando as cores detectadas no espectro vermelho, verde e azul (RGB) e suas respectivas porcentagens com base na distribuição de pixels. Os resultados também foram convertidos para o espaço de cores Lab.

Posteriormente, a cor também foi determinada utilizando o colorímetro HunterLab UltraScan PRO (Hunter Associate Laboratory Inc. Reston, EUA) operando com iluminante D 65 e ângulo de observação de 10°. O Sistema CIELab (L^*, a^* e b^*) foi usado, onde a variável L^* indica luminosidade, diferindo cores claras de escuras (onde: 0 – preto e 100 – branco) e as cromaticidade a^* e b^* comportam as informações de cor (onde: - a^* representa direção ao verde e + a^* direção ao vermelho, e - b^* representa direção ao azul e + b^* direção ao amarelo). Os valores L*, a* e b* foram convertidos para RGB usando o programa Nix Color Sensor. A diferença de cor (ΔE) entre as amostras foi calculada pela Equação 2, onde "0" significa os valores dos extrusados somente de farinha de arroz.

$$\Delta E = \sqrt{(L - L0)^2 + (a - a0)^2 + (b - b0)^2} \quad (2)$$

2.4.2 Umidade

A umidade dos extrusados foi determinada através da secagem em estufa a 105 °C até peso constante (AOAC, 2011).

2.4.3 Teor de Proteína

O teor de proteína dos extrusados foi obtido a partir da determinação de nitrogênio total pelo método de *Kjeldahl,* e utilizado fator de conversão 5,95 (AOAC, 2011).

2.4.4 Índice de expansão

O índice de expansão é expresso como a razão entre o diâmetro do produto extrusado e o diâmetro da matriz da extrusora (Faubion & Hoseney, 1982). O diâmetro do extrusado foi medido através de paquímetro digital e calculado conforme equação 3. A média de 10 medições aleatórias foi considerada como diâmetro do extrusado.

$$IE = \frac{D\ (mm)}{Do\ (mm)} \tag{3}$$

Onde, D o diâmetro do extrusado (mm) e Do o diâmetro da matriz (mm).

2.4.5 Densidade aparente

A densidade aparente (BD) foi determinada pela medida da dimensão dos extrusados usando paquímetro digital e determinada em razão da massa do extrusado (equação 4) é representada em g/cm³ (Alvarez-Martinez et al., 1988).

$$BD\ (g\ cm^{-3}) = \frac{4.m}{\pi.D^2.L} \tag{4}$$

Onde, m= a massa do produto extrusado (g), D o diâmetro (cm) e L o comprimento (cm).

2.4.6 Dureza

A dureza (N) dos extrusados foi avaliada usando um analisador de textura TA-XT2i Plus (Stable Micro Systems Ltd., Godalming, Reino Unido) equipado com uma lâmina de cisalhamento Warner-Bratzlerde com ranhura em 'V'. A distância de penetração foi fixada em 20 mm e a velocidade de teste foi de 2 mm s^{-1}, conforme Salvador-Reyes et al. (2022).

Os extrusados foram padronizados previamente em 5 cm de comprimento e a dureza definida como a força máxima necessária para ruptura das amostras. Os resultados foram

obtidos por uma média de quinze medições, sendo que a força para cortar foi o pico de força (N) alcançado durante o ensaio, representando a dureza.

2.4.7 Análise de imagem de seção transversal dos extrusados

A avaliação da imagem em corte foi realizada seguindo o método descrito por Sampaio et al. (2023), onde as imagens dos cortes transversais foram capturadas em scanner equipado com o software HP PreciseScan versão Pro 3.1 (HP Scanjet 4400C, Hewlett-Packard, EUA), utilizando papel de fundo azul. O diâmetro (mm), perímetro (mm), área (mm^2), número de células de ar, porosidade (%), circularidade do extrudado (0-1) e circularidade da célula de ar (0-1) foram determinados usando o Image-J (National Institute of Health, Bethesda, MD, EUA), sendo que o valor da circularidade indica que escala 0 é sem circularidade e escala 1 é um círculo perfeito. Os resultados foram obtidos pela média de dez extrusados.

2.4.8 Microscopia Eletrônica de Varredura (MEV)

A microestrutura interna de todas as amostras foi analisada por microscopia eletrônica de varredura (TM4000plus, Hitachi, Japão). Para a análise, os extrusados foram cortados verticalmente e horizontalmente, fixados em um *stub* de alumínio e estabilizado por uma fita adesiva dupla face de carbono. As imagens foram feitas na área central da peça extrudada em aumentos de 30x a 1500x e um grande número de capturas foi realizado para selecionar as mais representativas.

2.5 Caracterização tecno-funcional das farinhas pré-gelatinizadas de arroz e alga

Para obtenção da farinha pré-gelatinizada de farinha de arroz e algas marinhas os extrusados foram moídos em blender comercial (Hamilton Beach, modelo HBH450, United States), padronizadas a 60 *mesh* e acondicionadas em sacos de polietileno em condições atmosféricas para suas análises.

2.5.1 Propriedades de hidratação

O índice de absorção de água (IAA) e o índice de solubilidade em água (ISA) foram determinados pela metodologia de Anderson (1982). Para a análise foram pesados 2,5 g de amostra em tubos falcon de 50 mL, adicionado 30 mL de água destilada e agitado por um período de 30 min, após, os tubos foram centrifugados a 3000 rpm por 15 min. O sobrenadante resultante da centrifugação foi transferido para uma placa de alumínio e seco em estufa com

circulação de ar a 105ºC até peso constante e o IAA e ISA calculados pelas equações 5 e 6, respectivamente.

$$IAA = \frac{peso\ do\ resíduo\ de\ centrifugação\ (g)}{peso\ da\ amostra\ seca\ (g)}$$

$$ISA\ (\%) = \frac{Massa\ do\ resíduo\ da\ evaporação\ (g)}{peso\ da\ amostra\ seca\ (g)} * 100 \quad (6)$$

2.5.2 Capacidade de retenção de óleo

A capacidade de retenção de óleo (CRO) foi determinada (Lin, Humbert; Sosulski, 1974). Para a análise foram pesados 2,5g de amostra em tubos falcon de 50mL, adicionado 5 mL de óleo de soja a 25ºC. Os tubos foram homogeneizados de forma intermitente e posteriormente centrifugados a 2200 rpm durante 15 min. O sobrenadante foi removido por inversão do tubo e resultado expresso em g de óleo retidos em 1g de amostra.

$$CRO\ \left(g\frac{oil}{g}amostra\right) = \frac{óleo\ absorvido\ pela\ amostra\ (g)}{peso\ da\ amostra\ seca\ (g)} \quad (7)$$

2.5.3 Propriedades de pasta das farinhas extrusadas com algas e dureza da pasta

A propriedade de pasta foi analisada usando um Rapid Visco-Analyzer (modelo RVA-4500 da Perten Instuments, Warriewood, Austrália) com o software Thermocline for Windows versão 3, para determinar as propriedades de colagem das amostras utilizando o padrão de configuração *Extrusion 1* (AACCI, 2010). 3,5 g de amostra (14% de umidade) e 25 mL de água destilada foram colocadas em recipientes de alumínio específicos para o equipamento e acoplados ao RVA, onde permaneceram em agitação durante todo o experimento (20 min). Todas as determinações foram realizadas em triplicata e os parâmetros avaliadas foram pico frio (cP), pico bruto (cP), pico de espera (cP), quebra (cP), viscosidade final (cP), recuo (cP), tempo (min) e área de pico.

Para a dureza, as pastas obtidas foram armazenadas a 7 °C durante 24h no próprio recipiente de alumínio do RVA. As amostras foram mantidas em temperatura ambiente por cerca de 1 h antes da análise, retiradas do recipiente e a dureza da pasta determinada em um analisador de textura TA-XTplus (Stable Micro Systems, Haslemere, GBR), com uma carga de 50 kg usando uma porbe cilíndrica de 25 mm de diâmetro. A análise foi realizada em triplicata e os resultados expressos em N.

2.6 Avaliação dos compostos bioativos

As amostras das farinhas extrusadas foram solubilizadas com metanol (1 mg/mL) e submetidos a análise de capacidade sequestrante dos radicais DPPH. e ABTS+., redução de ferro FRAP e determinação de fenóis totais baseado em metodologias com pequenas modificações para leitora em microplacas (Mar et al., 2020).

Para o ensaio de DPPH, 10 µL da amostra foi adicionada a 190 µL da solução de DPPH (100 µM) e incubada em ambiente escuro por 30 min. Posteriormente foi realizada a leitura das absorbâncias em Leitora de Microplaca a 515 nm (Epoch 2, Agilent BioTek, Santa Clara, CA, EUA). Foi feita uma curva padrão de Trolox variando de 100 a 2000 µM (y = -0,0004x + 0,7353, R2 = 0,9965). No ensaio de ABTS, a amostra foi adicionada a solução de ABTS+ na proporção de 1:10 (v/v) e incubada em ambiente escuro por 6 min. Posteriormente foi realizada a leitura das absorbâncias em Leitora de Microplaca a 725 nm (Epoch 2, Agilent BioTek, Santa Clara, CA, EUA). Foi feita uma curva padrão de Trolox de 125 a 2000 µM (y = -0,0003x + 0,7344, R2 = 0,9997). Os resultados dos ensaios de capacidade de sequestro de radicais foram expressos em µM de Equivalentes de Trolox.

O ensaio de poder antioxidante redutor de ferro (FRAP) foi realizado com o reagente FRAP previamente preparado adicionando tampão acetato (0,3 mol L-1, pH = 3,6), solução de TPTZ (10 mM) e FeCl3.6H2O (20 mM), na proporção 10:1:1, conforme método de Pulido et al. (2020). Em microplaca, uma alíquota de 9 µL da amostra foi misturada com 27 µL de água ultrapura e adicionada a 270 µL do reagente FRAP. A microplaca foi incubada por 30 min a 37 ºC e a absorbância medida a 595 nm utilizando um Leitor de Microplaca (Epoch 2, Agilent BioTek, Santa Clara, CA, EUA). Os resultados foram obtidos pela equação de regressão da curva obtida a partir da solução padrão de sulfato ferroso de 250 a 2000 µM (y = 0,0009x - 0,1664, R2 = 0,9900) e expressos em µM Fe(II)/g de extrato.

O conteúdo fenólico total das algas marinhas foi determinado usando um método modificado de Folin-Ciocalteu (Velioglu et al., 1998). Para o ensaio, a amostra foi adicionada a mistura reacional (1:1) do reagente de Folin Ciocalteu e bicarbonato de sódio (6%), mantida no escuro por 90 min para posterior análise em Leitora de Microplaca a 750 nm (Epoch 2, Agilent BioTek, Santa Clara, CA, EUA). A curva padrão de ácido gálico foi feita de 31,2 a 1000 µg/mL (y = 0,0029x + 0,2373, R2 = 0,9938) e os resultados expressos em mg de equivalentes de ácido gálico por grama de amostra (mg EAG/g).

2.7 Análise estatística

A análise de variância (ANOVA) das médias foi realizada no software *Sisvar* versão 5.6 (Universidade Federal de Lavras, Lavras, MG, Brasil) com nível de significância de 95% e, quando significativa, o teste de Scott-Knott foi usado para determinar as diferenças estatísticas entre as médias ($p \leq 0,05$).

3. RESULTADOS E DISCUSSÃO

3.1 Caracterização tecno-funcional dos extrusados

A cor dos extrusados de arroz com adição de algas marinhas foi avaliada usando tanto imagens computadorizadas quanto um colorímetro. Os resultados são apresentados na Figura 3. Observa-se que a amostra R+SL apresentou os maiores valores de L* (48,73), indicando uma coloração mais clara em comparação com as outras amostras com algas (R+SD e R+SC). Esse resultado pode ser atribuído ao processo de liofilização, que preserva melhor a cor original dos alimentos (Subbiah et al., 2023). Por outro lado, a amostra R+SD apresentou uma coloração mais escura, provavelmente devido à possível oxidação dos pigmentos e à reação de Maillard durante a secagem a temperaturas mais elevadas.

A diferença de cor (ΔE) é uma medida importante para avaliar como a adição algas com diferentes métodos de secagem impactam a aparência dos snacks extrusados. O parâmetro ΔE reflete a variação em cada uma das três coordenadas cromáticas (L*, a* e b*) (Zhu et al., 2022). Valores mais altos de ΔE indicam uma maior diferença de cor em relação à referência, que neste caso é o snack feito somente de farinha de arroz (R). O valor baixo de ΔE no R (2.08) indica que não houve uma mudança significativa na cor durante o processamento na extrusora. A cor original da farinha de arroz é mantida de forma consistente, refletindo um processamento que não induz variações cromáticas perceptíveis.

Já a adição de algas liofilizadas resultou em uma diferença de cor moderada (ΔE = 9.33), esse valor sugere que, apesar da preservação da cor, as algas ainda alteram a aparência final do produto, adicionando tons esverdeados e marrons leves. Em contrapartida, os valores altos de ΔE nos extrusados R+SD e R+SC indicam mudança muito mais perceptíveis visualmente nos *snacks* quando comparados ao R.

A análise de cores realizada utilizando o software ImageJ forneceu uma perspectiva detalhada e quantitativa das cores presentes nos snacks (Figure 3). Os snacks R, R+SD, R+SL e R+SC apresentaram 39, 111, 113 e 122 cores distintas em sua superfície, respectivamente (Material suplementar). Em todos os snacks, a cor predominante foi marrom, com várias

tonalidades de marrom, onde no R+SD e R+SC as cores predominantes foram os tons de marrom mais escuros. Já no R+SL, houve aparecimentos de tonalidades verdes e marrom claro. Como a clorofila é mais sensível ao calor e está presente em concentração relativamente menor quando comparada à fucoxantina a tendência é que as algas secas por liofilização tenham tons mais esverdeados, como demonstrado nos estudos de Park et al. (2018) e Zhao et al. (2019).

A coloração dos produtos alimentares é um fator importante para a aceitação pelo consumidor, pois está diretamente relacionada à percepção de frescor, qualidade e sabor do produto final.

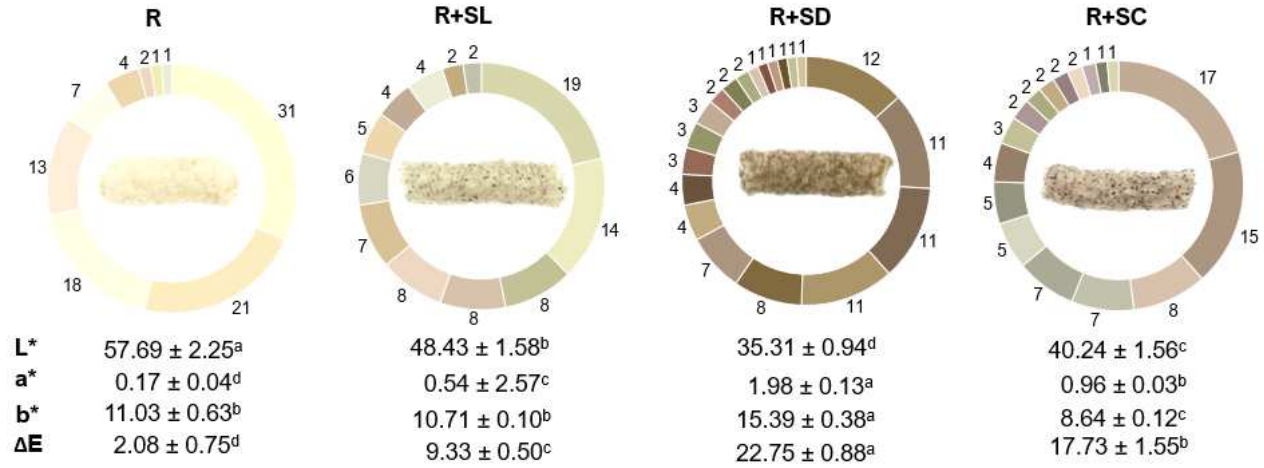

Figura 3. Cor dos extrusados de arroz e algas marinhas.

Os resultados são apresentados como média ± derivação padrão. Médias seguidas de letras diferentes na mesma linha diferem significativamente entre si pelo teste de comparações múltiplas de média Scott-Knott ($p<0,05$).

A Tabela 2 apresenta as propriedades tecno-funcionais dos extrusados de arroz com adição das algas marinhas. Em relação aos parâmetros do processo de extrusão, a SME foi maior para as amostras R e R+SD, enquanto R+SL e R+SC apresentaram valores significativamente menores. Esses resultados indicam que a adição de algas processadas por diferentes métodos de secagem influenciam a eficiência do processo de extrusão. Resultados semelhantes foram encontrados no estudo de Sampaio et al. (2023), onde elaboraram extrusados com diferentes concentrações de farinha de arroz e bambu e demonstraram que as fibras presentes na farinha de bambu geraram o aumento da SME durante o processo de extrusão. Uma maior SME favorece a gelatinização do amido e formação de bolhas, permitindo uma relação direta entre a SME e propriedades como densidade aparente e dureza (Oliveira et al., 2017).

A adição de algas marinhas aumentou o conteúdo de proteína dos extrusados. Comparativamente, a farinha de arroz tem um teor de proteína mais baixo, já as algas marinhas são compostas por um amplo espectro de aminoácidos, incluindo aqueles que são essenciais para a dieta humana, como lisina, leucina e isoleucina (Lorenzo et al., 2017), que são encontrados em quantidades relativamente baixas na farinha de arroz (Tagliapietra et al., 2024). As algas marinhas não só enriqueceram o produto final com proteínas, mas também melhoram a qualidade proteica devido aos aminoácidos essenciais presentes nas algas.

O índice de expansão foi maior no R, enquanto a adição de algas reduziu esse índice. Esses resultados podem ser relacionados ao teor de fibras alimentares das algas. A literatura demonstra que as partículas de fibra atuam como enchimentos e criam regiões de colapso, reduzindo o diâmetro das bolhas de ar e, consequentemente, afetando a expansão e a densidade aparente (Robin et al., 2011). A densidade aparente variou pouco entre as amostras, com valores próximos entre 0,40 g/cm³ e 0,46 g/cm³, no entanto foi menor nos snacks com adição de algas marinhas, o que pode ser relacionado ao teor de fibras. A expansão e a densidade são indicadores críticos da crocância e da sensação na boca de um alimento extrusado (Aghajanzadeh et al., 2024).

A dureza dos extrusados foi maior para R+SD (60,15 N), enquanto as outras amostras apresentaram valores significativamente menores, indicando que o método de secagem em estufa influencia a textura final dos snacks.

Ao examinar a microestrutura dos extrusados (Tabela 2 e Figura 4) observa-se que os extrusados apresentam uma elevada área (parte branca da imagem de 8bit) e baixa porosidade (parte em negrito da imagem de 8bit). A porosidade foi semelhante entre as amostras, sem diferenças estatisticamente significativas. Ainda, a tabela 2 demonstra que o snack R tem a maior área de seção transversal e que o perímetro segue um padrão semelhante à área, com a farinha de arroz pura apresentando os maiores valores.

A circularidade é relativamente constante entre as amostras, com valores menores que 1, demonstrando que a morfologia do extrusado é irregular de acordo com o coeficiente de circularidade presente na Tabela 2 e observado na Figura 4, o que indica uma menor formação de bolhas de ar durante a expansão.

Tabela 2. Propriedades tecno-funcionais dos extrusados de arroz e algas marinhas.

Propriedades	R	R+SD	R+SL	R+SC
Processo				
Torque (%)	49.55 ± 0.71^{a}	50.66 ± 1.41^{a}	47.66 ± 0.71^{a}	38.00 ± 4.95^{b}
SME (W.h/kg)	146.26 ± 3.02^{a}	151.42 ± 4.29^{a}	123.46 ± 5.62^{b}	119.60 ± 1.40^{b}
Extrusados				
Umidade (%)	5.35 ± 0.05^{d}	7.27 ± 0.21^{a}	6.05 ± 0.03^{c}	6.67 ± 0.15^{b}
Proteína (g/100g)[1]	8.87 ± 0.04^{b}	9.47 ± 0.32^{a}	9.43 ± 0.11^{a}	9.34 ± 0.12^{a}
Índice de expansão	2.79 ± 0.27^{a}	2.56 ± 0.18^{bc}	2.63 ± 0.11^{ab}	2.43 ± 0.08^{c}
Densidade (g cm^{-3})	0.46 ± 0.08^{a}	0.40 ± 0.04^{b}	0.40 ± 0.03^{b}	0.45 ± 0.03^{a}
Dureza (N)	21.85 ± 11.76^{b}	60.15 ± 10.52^{a}	30.33 ± 11.71^{b}	25.34 ± 11.87^{b}
Cor em RGB				
Seção-transversal				
Porosidade (%)	39.02 ± 18.75^{a}	40.54 ± 9.47^{a}	44.36 ± 12.11^{a}	31.96 ± 16.14^{a}
Área (mm^{2})	135.56 ± 10.86^{a}	99.14 ± 4.73^{b}	104.87 ± 8.90^{b}	87.48 ± 1.95^{c}
Perímetro (mm)	44.10 ± 1.88^{a}	37.80 ± 1.18^{c}	39.45 ± 1.60^{b}	35.85 ± 0.81^{d}
Circularidade	0.87 ± 0.02^{a}	0.87 ± 0.02^{a}	0.84 ± 0.04^{a}	0.85 ± 0.02^{a}
Diâmetro (mm)	13.22 ± 0.58^{a}	11.31 ± 0.31^{c}	11.80 ± 0.51^{b}	10.71 ± 0.40^{d}

Os resultados são apresentados como média ± derivação padrão. Médias seguidas de letras diferentes na mesma linha diferem significativamente entre si pelo teste de comparações múltiplas de média Scott-Knott ($p<0,05$). [1]O teor de proteína foi calculado considerando a amostra pronta para o consumo (6% de umidade).

A análise por MEV extrusados revelam detalhes sobre a morfologia das amostras, como pode ser visualizado na Figura 4. De forma geral, visualmente as amostras apresentaram-se bem semelhantes, com paredes relativamente finas e irregulares, contínuas, sem distinção entre macronutrientes, como amido e proteínas. No R pode-se observar uma superfície mais homogênea e lisa devido à natureza uniforme da farinha de arroz. Nas amostras R+SD, R+SL e R+SC pode-se observar a presença de pequenas rugosidades e alguns pontos mais heterogêneos. Essas rugosidades visíveis podem estar relacionada a presença de partículas ou fibras alimentares das algas. A espessura da parede e a porosidade são consideradas parâmetros de qualidade do extrusado, onde uma maior espessura ocasiona em uma menor porosidade o que aumenta a dureza do extrusado (Guillermic et al., 2021).

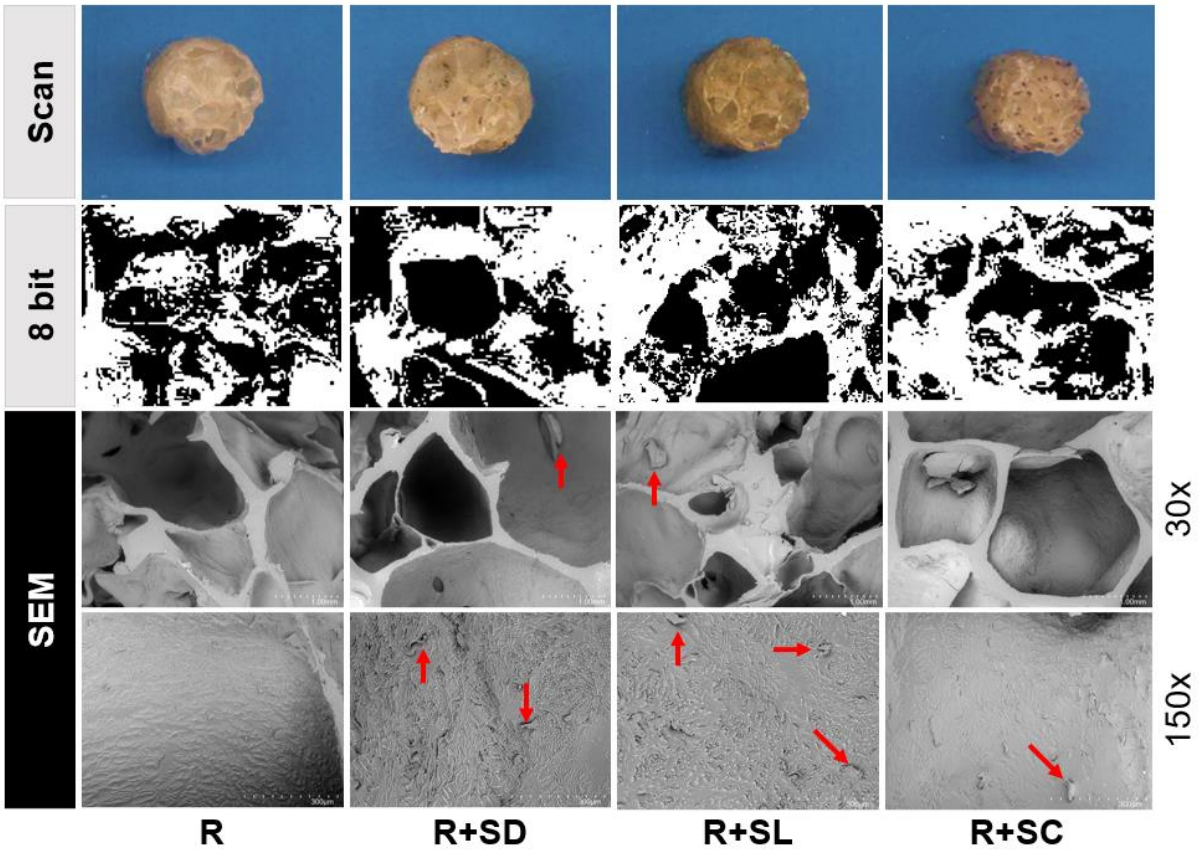

Figure 4. Imagens escaneadas transversais, área de porosidade de 8 bits e capturas do MEV em 30× e 1500× de extrusados de farinha de arroz com algas marinhas. Setas em vermelho mostram detalhes da parede dos alvéolos, com destaque para pontos irregulares na parede.

3.2 Caracterização tecno-funcional das farinhas pré-gelatinizadas de arroz e alga marinha

A caracterização tecno-funcional das farinhas pré-gelatinizadas de arroz e alga marinha envolveu a análise de diversas propriedades que influenciam diretamente o desempenho dessas farinhas em aplicações alimentares.

As propriedades tecnofuncionais de absorção (IAA) e solubilidade em água (ISA), retenção de óleo (CRO) estão apresentadas na Figura 5. A amostra R+SL apresentou o maior índice de absorção de água (Figura 5A), Isso sugere que as algas secas por liofilização aumentam a capacidade da farinha de arroz de absorver água, possivelmente devido à maior retenção de estruturas celulares e compostos hidrofílicos. A amostra R+SD apresentou o maior ISA(%) (Figura 5B), indicando que a secagem em estufa pode aumentar a solubilidade dos componentes da farinha na água. Isso pode ser devido à degradação parcial de macromoléculas durante a secagem em estufa, tornando-as mais solúveis. Em geral, a farinha de arroz pré-gelatinizada mostra uma boa capacidade de absorção de água, com valores que variam de 6,97

a 9,02, devido à sua estrutura modificada pelo processo extrusão (Silva Clerici & El-Dash, 2008).

O IAA e o ISA variam conforme o grau de gelatinização e dextrinização que o amido sofre durante o processo de extrusão. Quando a gelatinização é mais intensa, há um aumento no número de grupos hidroxila disponíveis para formar ligações de hidrogênio com a água, resultando em um IAA mais alto. Por outro lado, a dextrinização aumenta a degradação das moléculas de amido em dextrinas menores e mais solúveis, o que leva a um ISA mais elevado (Silva Clerici & El-Dash, 2008; Yu et al., 2017).

A amostra R apresentou a maior CRO (Figura 5C), enquanto as amostras com adição de algas (R+SD, R+SL, R+SC) apresentaram menores capacidades. Isso sugere que a adição de algas pode reduzir a capacidade da farinha de arroz de reter óleo, possivelmente devido à presença de componentes das algas que interagem com o óleo de maneira diferente do amido de arroz puro.

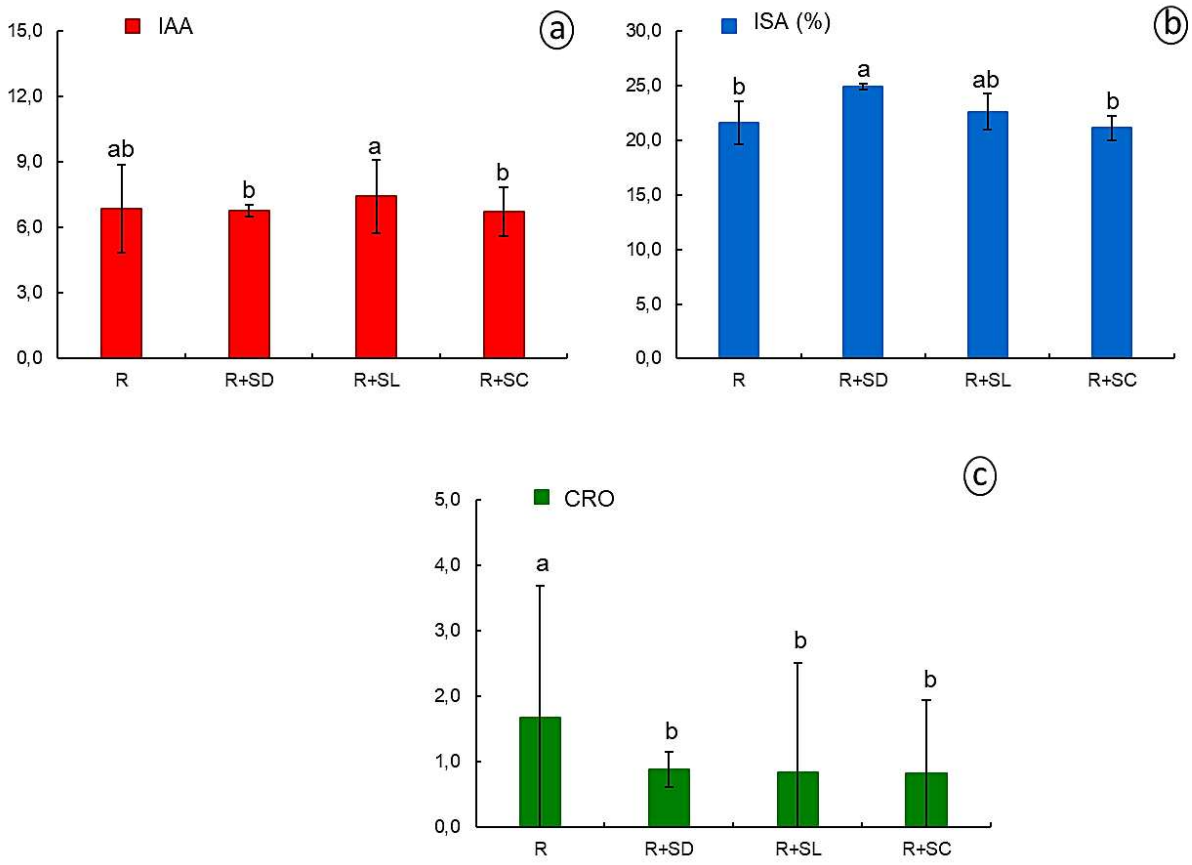

Figura 5. IAA, ISA e CRO das farinhas pré-gelatinizadas de arroz e algas marinhas obtidas pelo processo de extrusão termoplástica.

A figura 6 apresenta o termograma da análise de DSC, onde pode-se observar as curvas das transições térmicas dos materiais. A farinha de arroz contém amido, cuja gelatinização, é um fator crítico na extrusão. Os resultados da análise demonstraram que a temperatura inicial de transição (T0 onset) da amostra R foi 58,86ºC, sendo o pico em 65,2ºC. O ΔH negativo (-1,13) indicou que a reação é exotérmica com liberação de energia. Era esperado que a presença das algas, por ter composição diferente do amido, alterassem a estrutura do amido e/ou modificassem suas propriedades térmicas. Pelo gráfico (Figura 6), pode-se observar que em todas as amostras com algas (R+SD, R+SL e R+SC) não foram detectados picos, sendo semelhantes entre si. Esses achados podem estar relacionada à quantidade significativa de fibras alimentares e minerais, cuja resistência térmica pode ser maior do que a usada no DSC que foi de até 130º C.

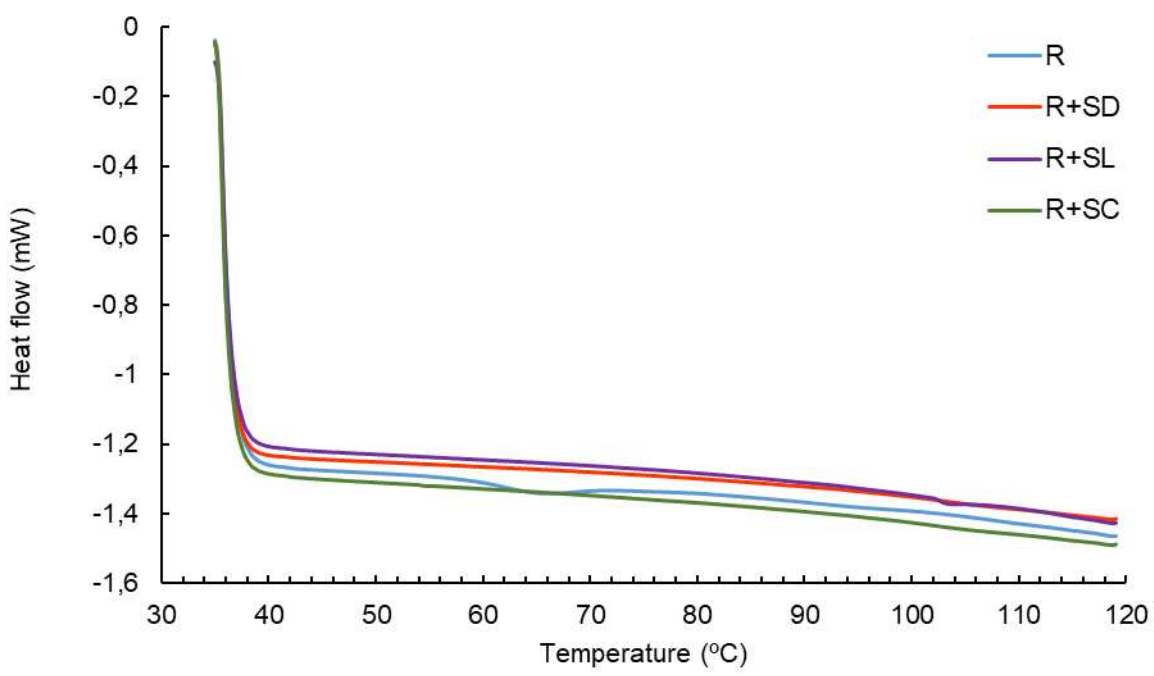

Figura 6. Termogramas DSC das farinhas pré-gelatinizadas de arroz com algas marinhas.

A Tabela 6 apresenta as propriedades das massas das formulações e dos extrusados de farinha de arroz e algas marinhas. As propriedades da pasta permitem avaliar o impacto dos processos e o quanto eles são capazes de modificar o amido (Magallanes-Cruz et al., 2023). Na sua forma nativa, os selecionadores de amido apresentam baixa solubilidade em água à temperatura ambiente, mas quando a temperatura de gelatinização é atingida pode-se observar

um aumento na particularidade (Sampaio et al., 2023). No geral, pode-se observar diferenças significativas ($p<0,05$) entre as farinhas para a propriedade de massas alimentícias (Tabela 6).

Para as formulações, pode-se observar que em relação a particularidades frias não houve diferenças significativas, indicando que a adição de algas não altera particularidades iniciais da massa. Em relação ao pico de espera, os valores são bastante próximos, variando de 3640,66 (R+SD) a 3813,00 (R+SC), isso indica que a capacidade de manter a interferência durante o cozimento é semelhante entre as amostras. Os valores de quebra variaram de 796.33 (R+SD) a 1361.00 (R+SL), sendo que a menor quebra foi observada na amostra R+SD, demonstrando uma estabilidade maior da massa durante o cozimento.

As amostras R e R+SL obtiveram as maiores viscosidades finais. A viscosidade final aumentou em relação ao pico, isso ocorre porque há uma reorganização das cadeias de amilose e amilopectina através das ligações de hidrogênio, formando gel e sinérese e assim as características da retrogradação do amido (Sajilata & Singhal, 2005). O tempo de pico e a área do pico frio foram semelhantes entre todas as amostras, não apresentando diferenças importantes.

Nas farinhas extrusadas, o pico frio e o pico bruto foram maiores nas amostras R+SD e R+SL. Esses resultados podem ser explicados pela interação dos polissacarídeos e proteínas das algas *Sargassum* sp. com o amido de arroz, potencializado pelo processo de extrusão. O processo de extrusão envolve alta temperatura e pressão, o que pode alterar a estrutura das macromoléculas, como amidos e proteínas (Leonel, 2004). Isso pode resultar em diferentes comportamentos de peculiaridades ao serem reidratadas e renovadas novamente no RVA. A maior ocorrência final observada nas amostras R+SL e R+SC. Os polissacarídeos presentes nas algas (como alginatos, carragenanas e fucoidanas) possuem propriedades viscosas e gelificantes que podem aumentar a proporção final da massa. A preservação desses componentes na liofilização (SL) e nos processos comerciais (SC) pode ser maior do que na secagem em estufa. Além disso, os polissacarídeos das algas podem ter atuado inibindo a sinérese durante o resfriamento, mantendo a massa mais coesa e com maior interferência final.

A Tabela 7 apresenta os resultados da capacidade antioxidante (DPPH, ABTS, FRAP) e o conteúdo de fenóis totais (FT) das farinhas extrusadas de arroz com algas marinhas. A amostra R+SL apresentou a maior capacidade de sequestro de radicais DPPH, esse resultado pode ser atribuído à preservação eficaz de compostos antioxidantes durante o processo de liofilização (Silva et al., 2021; Subbiah et al., 2023). A amostra R apresentou o maior ABTS. A amostra R+SC apresentou o maior poder redutor de ferro. Os fenóis totais não foram detectados (nd)

em nenhuma das amostras, isso indica que a concentração de fenóis está abaixo do limite de detecção do método empregado.

Tabela 7. Compostos bioativos dos extrusados de farinha de arroz e algas marinhas.

Amostras	DPPH (µmol TE/g)	ABTS (µmol TE/g)	FRAP (µmol TE/g)	FT (mg GAE/g)
R	118.08 ± 5.77^{c}	301.11 ± 10.72^{a}	337.85 ± 2.57^{d}	nd
R+SD	98.08 ± 5.20^{d}	194.44 ± 11.71^{c}	356.37 ± 3.57^{b}	nd
R+SL	147.25 ± 6.61^{a}	166.67 ± 8.82^{d}	347.85 ± 2.80^{c}	nd
R+SC	128.08 ± 5.20^{b}	264.44 ± 11.71^{b}	366.37 ± 3.90^{a}	nd

Os resultados são apresentados como média ± derivação padrão. Médias seguidas de letras diferentes na mesma linha diferem significativamente entre si pelo teste de comparações múltiplas de média Scott-Knott ($p<0,05$). nd = não detectado.

Embora o estudo tenha sido bem amplo e avaliado as propriedades tecno-funcionais dos extrusados e das farinhas extrusadas com algas marinhas, algumas limitações precisam ser destacadas. Futuras pesquisas devem incluir testes de aceitação sensorial com diferentes segmentos de consumidores para identificar preferências e possíveis melhorias nos produtos. Além disso, o estudo foi realizado em escala laboratorial, a extrapolação dos resultados para uma escala industrial pode apresentar desafios, como a eficiência energética, custo de produção e consistência do produto final em grandes lotes. Outro fator importante é a limitação geográfica das amostras estudadas, visto que as algas marinhas utilizadas neste estudo foram coletadas em uma localização específica (Praia das Cigarras, São Sebastião, SP, Brasil) e sabe-se que há variabilidade na composição química das algas devido a diferentes locais de coleta ou condições ambientais, o que pode influenciar a generalização dos resultados encontrados.

Tabela 6. Propriedades e dureza da pasta das formulações e dos extrusados de farinha de arroz e algas marinhas.

Amostras	Pico frio (cP)	Pico bruto (cP)	Pico de espera (cP)	Quebra(cP)	Viscosidade final (cP)	Recuo (cP)	Tempo de pico (min)	Área de pico	Dureza (N)
Formulação									
R	82.00 ± 1.73^{a}	4975.33 ± 6.47^{a}	3709.00 ± 4.47^{a}	1266.33 ± 9.48^{a}	9873.33 ± 9.30^{a}	6164.33 ± 1.42^{a}	8.24 ± 0.04 ^{a}	27.83 ± 3.08^{a}	9.13 ± 0.06^{a}
R+SD	78.66 ± 6.17^{a}	4437.00 ± 2.86^{b}	3640.66 ±9.50 ^{a}	796.33 ± 2.61^{b}	9087.00 ± 4.67^{c}	5446.33 ± 4.67^{b}	8.15 ± 0,10^{a}	65.76 ± 8.42^{a}	7.99 ± 0.31^{b}
R+SL	63.00 ± 5.08^{a}	5040.33 ± 7.14^{a}	3679.33 ± 1.57 ^{a}	1361.00 ± 1.50^{a}	10003.66 ± 2.77^{a}	6324.33 ± 2.77^{a}	8.09 ± 0,03 ^{a}	39.62 ± 6.51^{a}	8.81 ± 0.14^{a}
R+SC	67.33 ± 5.81^{a}	4922.00 ± 8.04^{a}	3813.00 ± 6.56^{a}	1109.00 ± 3.64^{a}	9643.33 ± 4.04^{b}	5830.33 ± 4.04^{b}	8.06 ± 0,07 ^{a}	44.93 ± 6.60^{a}	8.47 ± 0.54^{b}
Extrusados									
R	1123.33 ± 9.81^{b}	1027.00 ± 3.51^{b}	121.66 ± 4.26^{a}	905.33 ± 7.75^{b}	644.66 ± 5.50^{b}	523.00 ± 5.50^{b}	2.07 ± 0,00^{a}	2035.99 ± 3.89^{b}	2.12 ± 0.20^{a}
R+SD	1314.66 ± 5.48^{a}	1269.00 ± 7.33^{a}	120.66 ± 5.03^{a}	1148.33 ± 5.35^{b}	641.66 ± 2.55^{b}	521.00 ± 2.55^{b}	2.11 ± 0.03^{a}	2357.53 ± 8.22^{a}	1.63 ± 0.08^{a}
R+SL	1280.33 ± 2.35^{a}	1179.00 ± 7.35^{a}	187.33 ± 4.99^{a}	991.66 ± 2.15^{a}	822.66 ± 2.03^{a}	635.33 ± 2.03^{a}	2.35 ± 0.34^{a}	2243.86 ± 2.13^{a}	2.18 ± 0.17^{a}
R+SC	1128.00 ± 7.83^{b}	945.33 ± 9,72^{b}	167.66 ± 7.56^{a}	777.66 ± 2.16^{a}	802.00 ± 8.59^{a}	634.33 ± 8.59^{a}	2.17 ± 0.08^{a}	1884.84 ± 2.30^{b}	1.94 ± 0.41^{a}

Os resultados são apresentados como média ± derivação padrão. Médias seguidas de letras diferentes na mesma coluna diferem significativamente entre si pelo teste de comparações múltiplas de Scott-Knott ($p<0,05$). As formulações foram comparadas entre si e os extrusados também foram comparados entre si.

5. CONCLUSÃO

A incorporação da alga marinha *Sargassum* sp. em farinhas de arroz extrusadas pode melhorar as propriedades tecno-funcionais e bioativas dos produtos finais. A adição de algas marinhas secas por liofilização, aumentou o IAA e a atividade antioxidante das farinhas. A análise de cor revelou que a amostra com algas liofilizadas manteve uma coloração mais clara. O MEV mostrou que a presença de algas introduziu rugosidades e heterogeneidade na superfície dos extrusados, indicando a integração das fibras das algas na matriz do amido. Esses resultados indicam que diferentes métodos de secagem das algas impactam as propriedades finais das farinhas/produtos.

Os achados deste estudo demonstram o potencial das algas marinhas como ingredientes funcionais em produtos extrusados, contribuindo para o desenvolvimento de alimentos mais saudáveis e nutritivos. A escolha do método de secagem das algas é importante para otimizar as propriedades funcionais e bioativas dos produtos finais, com a liofilização se mostrando mais eficaz na preservação de compostos antioxidantes e na melhoria das propriedades tecno-funcionais.

Este estudo abre caminhos para futuras pesquisas focadas na utilização de algas marinhas em diferentes matrizes alimentares e tecnologias de processamento, visando sempre o desenvolvimento de produtos com valor agregado e benefícios à saúde. A adição de algas não só enriquece o perfil nutricional dos produtos, mas também pode melhorar suas propriedades sensoriais e tecno-funcionais.

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Material suplementar 1. Análise de cor

	R				R+SD				R+SL				R+SC			
	R	**G**	**B**	**%**	**R**	**G**	**B**	**%**	**R**	**G**	**B**	**%**	**R**	**G**	**B**	**%**
1	255	255	216	31,288	216	216	172	18,765	150	128	84	11,804	194	172	150	17,297
2	255	238	194	21,218	238	238	194	14,224	150	128	106	11,267	172	150	128	14,882
3	255	255	230	17,785	194	194	150	8,076	128	106	84	11,014	216	194	172	8,148
4	255	238	216	12,685	216	194	172	7,529	172	150	106	10,855	194	194	172	6,785
5	255	255	238	6,529	238	216	194	7,521	128	106	62	7,944	172	172	150	6,565
6	238	216	172	4,498	216	194	150	7,482	172	150	128	6,727	216	216	194	5,139
7	238	216	194	1,533	216	216	194	5,941	194	172	128	4,167	150	150	128	4,561
8	240	240	180	1,427	238	216	172	4,908	106	84	62	3,555	150	128	106	4,256
9	238	238	216	1,249	194	172	150	4,397	150	106	84	3,099	194	194	150	2,986
10	255	255	194	0,907	238	238	216	4,333	150	150	106	3,022	172	150	150	2,305
11	238	216	150	0,178	194	172	128	2,413	194	172	150	2,905	172	172	128	1,846
12	255	238	172	0,133	194	194	172	2,076	172	128	106	1,977	194	172	128	1,807
13	255	238	238	0,103	172	172	128	0,969	128	128	84	1,963	150	128	128	1,727
14	238	238	238	0,077	255	238	216	0,941	172	172	128	1,6	238	216	194	1,653
15	238	255	216	0,076	255	255	216	0,911	216	194	172	1,216	194	172	172	1,489
16	216	216	172	0,051	172	150	128	0,88	128	84	62	1,177	128	128	106	1,264
17	255	255	255	0,045	255	255	238	0,81	194	150	128	1,155	216	216	172	1,226
18	238	194	150	0,034	172	172	150	0,737	106	84	40	1,148	216	194	194	0,958
19	255	216	194	0,029	216	238	194	0,562	194	194	150	1,102	128	106	106	0,871
20	255	216	172	0,027	238	238	238	0,56	216	194	150	1,079	238	238	216	0,865
21	216	194	150	0,019	216	216	150	0,406	106	106	62	0,749	172	150	106	0,835
22	238	194	172	0,015	150	128	106	0,379	128	128	106	0,673	194	150	128	0,818
23	216	194	172	0,013	150	150	128	0,353	238	238	238	0,657	216	194	150	0,816
24	216	216	150	0,011	238	255	216	0,273	84	62	40	0,654	238	238	238	0,739
25	216	216	194	0,011	172	150	106	0,268	216	216	194	0,616	150	150	106	0,639
26	255	216	106	0,008	128	128	106	0,251	194	194	172	0,515	128	106	84	0,63
27	255	216	128	0,007	255	255	255	0,203	216	216	172	0,507	106	106	84	0,61
28	255	216	150	0,005	255	238	194	0,199	150	150	128	0,493	106	84	84	0,56
29	238	255	194	0,005	128	106	84	0,197	172	128	84	0,461	84	62	62	0,538
30	255	238	150	0,005	238	238	172	0,195	172	172	150	0,456	62	62	62	0,477
31	238	255	238	0,005	216	216	216	0,192	106	106	84	0,387	62	40	40	0,469
32	238	216	216	0,003	106	106	84	0,18	150	106	62	0,385	40	40	40	0,38
33	238	194	128	0,003	106	84	62	0,16	194	150	106	0,312	238	216	216	0,367
34	255	194	106	0,002	194	194	128	0,129	238	238	216	0,256	84	84	84	0,335
35	255	194	128	0,002	150	150	106	0,124	238	216	194	0,223	216	216	216	0,313
36	194	172	150	0,002	84	84	62	0,118	106	62	40	0,208	106	106	106	0,307
37	216	172	128	0,001	194	216	172	0,117	128	106	106	0,204	194	194	194	0,293
38	216	238	194	0,001	84	62	62	0,105	255	255	238	0,187	84	84	62	0,249
39	238	216	128	0,001	128	106	106	0,09	216	216	216	0,176	255	255	238	0,246
40					194	194	194	0,087	216	172	150	0,171	216	172	150	0,242
41					106	84	84	0,083	84	84	62	0,166	150	150	150	0,224
42					216	172	150	0,082	255	255	255	0,158	172	128	106	0,222
43					62	62	62	0,082	106	84	84	0,134	238	238	194	0,219
44					238	255	238	0,081	216	194	194	0,132	106	84	62	0,212
45					255	238	238	0,081	238	216	216	0,119	194	150	150	0,208
46					62	40	40	0,08	84	62	62	0,118	255	255	255	0,206
47					216	238	216	0,08	172	150	150	0,117	128	128	128	0,201
48					194	150	128	0,072	172	150	84	0,112	62	62	40	0,201
49					216	194	194	0,071	194	172	172	0,109	172	172	172	0,175
50					62	62	40	0,067	255	238	238	0,108	255	238	238	0,15
51					238	216	216	0,061	62	62	40	0,106	172	128	128	0,142
52					150	128	128	0,059	150	128	128	0,101	84	62	40	0,11
53					84	62	40	0,058	62	40	18	0,1	62	40	62	0,091
54					194	172	172	0,052	62	40	40	0,098	150	106	106	0,077
55					84	84	84	0,05	84	84	40	0,086	84	62	84	0,071
56					40	40	40	0,05	128	84	40	0,085	216	172	172	0,064
57					106	106	106	0,047	194	194	194	0,085	40	40	18	0,063
58					172	150	150	0,041	216	172	128	0,064	150	128	84	0,063
59					150	128	84	0,039	150	106	106	0,063	150	106	84	0,052
60					172	172	172	0,036	128	84	84	0,059	106	62	62	0,049
61					172	128	106	0,036	194	172	106	0,058	255	238	216	0,048
62					172	194	150	0,034	150	128	62	0,055	128	128	84	0,044
63					128	128	84	0,031	172	172	172	0,052	238	216	172	0,043

64	128	128	128	0,031	238	238	194	0,05	128	84	84	0,04
65	194	216	194	0,031	106	62	62	0,049	40	18	18	0,037
66	194	150	106	0,029	238	216	172	0,049	62	40	18	0,034
67	216	194	128	0,029	150	150	84	0,041	84	40	40	0,033
68	150	150	150	0,029	194	194	128	0,039	106	84	106	0,032
69	128	106	62	0,023	150	150	150	0,032	40	40	62	0,024
70	150	106	84	0,021	172	172	106	0,032	40	18	40	0,023
71	216	238	172	0,02	40	40	18	0,028	62	62	84	0,02
72	40	40	18	0,02	84	62	18	0,023	238	194	172	0,018
73	238	216	150	0,019	128	128	62	0,018	172	194	150	0,016
74	62	40	18	0,019	40	18	18	0,018	150	172	150	0,015
75	128	84	62	0,019	172	128	128	0,018	128	84	62	0,015
76	216	172	128	0,018	128	128	128	0,015	194	216	194	0,015
77	238	194	172	0,017	84	40	40	0,015	172	194	172	0,014
78	106	106	62	0,017	216	194	128	0,015	128	106	128	0,013
79	194	172	106	0,016	40	40	40	0,014	84	106	84	0,012
80	106	62	40	0,015	128	106	40	0,012	106	128	106	0,011
81	40	18	18	0,015	194	150	150	0,012	216	238	194	0,011
82	106	62	62	0,012	216	216	150	0,012	194	216	172	0,011
83	150	172	128	0,012	106	106	106	0,011	150	128	150	0,01
84	172	172	106	0,009	238	255	238	0,011	62	18	18	0,01
85	128	84	84	0,008	84	40	18	0,01	216	238	216	0,009
86	150	172	150	0,008	62	62	18	0,009	84	84	106	0,009
87	150	106	106	0,008	106	106	40	0,009	106	106	62	0,008
88	84	40	40	0,007	62	62	62	0,009	106	62	40	0,007
89	238	194	150	0,007	216	238	216	0,008	150	172	128	0,006
90	172	194	172	0,007	84	84	84	0,008	194	150	106	0,006
91	194	216	150	0,007	216	172	172	0,006	172	150	172	0,006
92	18	18	18	0,006	255	238	216	0,006	238	255	238	0,006
93	172	128	84	0,006	194	216	194	0,005	40	62	62	0,005
94	106	84	40	0,005	172	194	172	0,005	255	255	216	0,005
95	172	128	128	0,005	238	194	172	0,005	194	172	194	0,005
96	255	255	194	0,005	172	194	150	0,004	106	106	128	0,005
97	106	128	106	0,005	194	216	172	0,003	128	106	62	0,005
98	62	40	62	0,005	40	18	0	0,003	128	150	128	0,004
99	128	150	128	0,004	216	238	194	0,003	40	62	40	0,004
100	84	106	84	0,004	62	18	18	0,003	238	194	194	0,004
101	84	40	18	0,003	255	238	255	0,002	62	84	84	0,003
102	84	62	84	0,003	216	194	216	0,002	84	40	62	0,003
103	128	150	106	0,003	150	172	150	0,002	62	18	40	0,003
104	172	150	84	0,003	128	150	128	0,002	128	128	150	0,003
105	84	84	40	0,002	238	216	238	0,002	106	62	84	0,003
106	150	106	62	0,002	194	172	194	0,002	62	84	62	0,003
107	62	84	62	0,002	62	40	0	0,002	216	194	216	0,002
108	40	18	40	0,002	255	238	194	0,001	150	150	172	0,002
109	62	18	18	0,002	150	128	150	0,001	172	128	84	0,002
110	40	40	62	0,002	128	106	128	0,001	172	106	62	0,002
111	84	84	106	0,001	40	18	40	0,001	216	172	128	0,002
112					238	194	150	0,001	84	62	106	0,002
113					150	172	128	0,001	106	84	128	0,002
114									62	40	84	0,002
115									84	106	106	0,002
116									18	40	40	0,001
117									255	238	194	0,001
118									238	216	238	0,001
119									18	40	18	0,001
120									172	106	84	0,001
121									255	238	255	0,001
122									18	18	18	0,001

3 DISCUSSÃO GERAL

O presente trabalho teve como objetivo principal caracterizar a alga marinha parda *Sargassum* sp. coletada no litoral de São Paulo, Brasil, quanto às suas propriedades nutricionais e tecno-funcionais utilizando dois métodos de secagem e avaliar o potencial de aplicação desta alga em produtos extrusados.

A revisão inicial da literatura serviu como base e ressaltou a importância das algas marinhas como fontes promissoras de nutrientes e biocompostos, destacando sua capacidade de melhorar tanto as propriedades nutricionais quanto tecnofuncionais de diversos produtos alimentícios. Estudos prévios indicam que a incorporação de algas marinhas pode aumentar significativamente o teor de fibras, proteínas, ácidos graxos ômega-3, compostos fenólicos, carotenoides, vitaminas e minerais nos alimentos, contribuindo para dietas mais saudáveis e funcionais. Os métodos de secagem das algas, como secagem ao sol e em estufas, foram discutidos em termos de suas implicações na composição nutricional e funcional. A secagem foi considerada fundamental para inativar sistemas enzimáticos, inibir o crescimento microbiano e reduzir o volume de armazenamento, tornando o processo mais sustentável. O artigo também abordou a aplicação das algas marrons em diferentes grupos de alimentos, como produtos cárneos, laticínios, panificação e bebidas. A adição de algas poderia melhorar a retenção de água, estabilidade de emulsões, perfil nutricional e capacidade antioxidante dos produtos. O artigo também abordou a aplicação das algas marrons em diferentes grupos de alimentos, como produtos cárneos, laticínios, panificação e bebidas. No entanto, a revisão revelou lacunas significativas, especialmente no que diz respeito ao uso das algas em sua forma integral, como farinha. Poucos estudos utilizam a alga *Sargassum* sp., e não foram encontrados estudos realizados no Brasil.

A partir dessa revisão, surgiu outros "*insights*", como a necessidade de investigar o amido presente nas algas, conforme relatado em alguns estudos. Assim, foi dada continuidade à revisão que abordou detalhadamente esse tema. A revisão mostrou que as algas verdes, como a espécie *Ulva*, foram sugeridas como uma fonte promissora para a extração de amido, apesar dos desafios associados à quebra das paredes celulares e ao isolamento dos grânulos de amido. Os grânulos de amido de algas são pequenos (1.7–7 μm) e apresentam alto teor de amilose (acima de 55%), indicando que podem ser amidos resistentes ou de digestão lenta, com propriedades nutricionais vantajosas. A revisão ressalta que é necessário mais investimento em pesquisa para elucidar a estrutura molecular, propriedades tecnológicas e aspectos nutricionais

do amido das macroalgas, além de regulamentações para a produção e comercialização de materiais derivados de algas.

Pensando numa futura aplicação das algas marinhas, identificamos o arroz como uma excelente matriz alimentar. O arroz é um dos alimentos mais consumidos no mundo, sendo a base da dieta de bilhões de pessoas. Sua versatilidade, perfil nutricional e o seu sabor neutro o tornam uma excelente matriz alimentar para o desenvolvimento de produtos inovadores. Nesse contexto buscou-se, de uma forma bem ampla, estudar as propriedades nutricionais e os tipos de beneficiamento do arroz e seu impacto nos aspectos nutricionais. A revisão demonstrou que a composição nutricional do arroz varia conforme o tipo de processamento industrial. O artigo descreve os processos de obtenção de arroz integral, arroz polido e arroz parboilizado. Após a remoção da casca, obtém-se tanto o arroz integral quanto o arroz polido, ambos podendo ser também parboilizados. Produtos derivados, como farinha e amido de arroz, expandem o mercado deste cereal devido às suas características hipoalergênicas e sem glúten. A revisão aponta a importância de continuar promovendo a pesquisa e o desenvolvimento de novos produtos derivados do arroz para atender às necessidades nutricionais e tecnológicas do mercado.

A caracterização da alga marinha *Sargassum* sp., coletada na costa de São Paulo, Brasil, foi realizada, utilizando dois métodos de secagem, secagem em estufa (SD) e liofilização (SL). Uma amostra comercial desidratada (SC) foi utilizada como controle. A pesquisa demonstrou que esta alga possui propriedades nutricionais valiosas, destacando-se por seu alto teor de fibras, proteínas e minerais, além de suas excelentes propriedades antioxidantes e tecnofuncionais quando liofilizadas. Estas características tornam a *Sargassum* sp. um ingrediente potencialmente útil para a indústria alimentícia, especialmente em produtos que visam melhorar o valor nutricional e funcionalidade. A liofilização se mostrou um método eficaz para preservar as propriedades nutricionais e antioxidantes das algas, embora seja um processo mais caro e de alto consumo energético. No entanto, os benefícios nutricionais e funcionais das farinhas liofilizadas podem justificar esses custos adicionais, dependendo da aplicação industrial. Cabe destacar que o estudo focou não abordou a bioacessibilidade e a bioatividade dos compostos bioativos presentes nas algas no corpo humano, sendo uma lacuna para futuros estudos.

Por fim, foi avaliado o potencial das algas marinhas como ingredientes funcionais em produtos extrusados de farinha de arroz. O estudo demonstrou que a incorporação de *Sargassum* sp. pode melhorar significativamente as propriedades tecno-funcionais e bioativas dos produtos

finais. A liofilização se mostrou mais eficaz na preservação de compostos antioxidantes e na melhoria das propriedades tecno-funcionais, como a capacidade de retenção de água e a cor dos produtos. A adição de algas marinhas também aumentou o conteúdo de proteína dos extrusados, enriquecendo o produto final com aminoácidos essenciais. A presença de fibras das algas reduziu o índice de expansão e a capacidade de retenção de óleo, o que pode impactar a textura e a crocância dos *snacks* extrusados. Para complementar essa investigação, é necessário conduzir testes sensoriais para avaliar a aceitação dos produtos extrusados com adição de algas, incluindo avaliações de sabor, textura, aparência e preferência geral. No entanto, este estudo abre o caminho para futuras investigações centradas no uso de algas marinhas em diversas matrizes alimentares e tecnologias de processamento, com o objetivo constante de desenvolver produtos que ofereçam valor agregado e benefícios à saúde.

4 CONCLUSÃO

A pesquisa sobre algas marinhas, em especial a alga parda *Sargassum* sp., destaca-se como uma fronteira inovadora e essencial no campo da ciência dos alimentos e da nutrição. Esse trabalho explorou de forma abrangente as propriedades nutricionais e tecno-funcionais da alga, bem como seu potencial de aplicação em produtos extrusados, proporcionando avanços significativos para a indústria alimentícia. A importância deste estudo é ressaltada pela crescente demanda global por alimentos que sejam simultaneamente saudáveis, funcionais e sustentáveis. As algas marinhas emergem como uma solução promissora para esses desafios, alinhando-se perfeitamente com os ODS. A capacidade das algas marinhas de crescerem sem a necessidade de terras aráveis, fertilizantes ou pesticidas, reforça sua relevância ambiental e sustentabilidade. O estudo das algas marinhas é, sem dúvida, um campo desafiador, mas com um potencial transformador para a inovação alimentar.

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ANEXOS

Anexo I: AUTORIZAÇÃO DO PERIÓDICO FOOD RESEARCH INTERNATIONAL

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[FST] Editor Decision

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Dom, 17/03/2024 00:29
Para:Bruna Lago Tagliapietra <bruna_tagliapietra@hotmail.com>;Maria Teresa Pedrosa Silva Clerici <mclerici@unicammp.br>

Bruna Lago Tagliapietra, Camille Flores Soares, Maria Teresa Pedrosa Silva Clerici:

We have reached a decision regarding your submission to Food Science and Technology, "Rice (Oryza sativa L.) and its products for human consumption: general characteristics, nutritional properties, and types of processing".

Our decision is to: Accept Submission

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