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REVIEW

Industrial and biotechnological applications of red algae: a systematic mapping

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ABSTRACT. The study aimed to systematically and informatively map the different applications of red algae, as well as to discuss the challenges and opportunities for advancement in this field. Specific knowledge gaps and promising areas were also identified to guide future research and practical applications. Data were collected through four renowned scientific databases: Web of Science, SciELO, ScienceDirect, PubMed, and Scopus. Using specific descriptors, all publications were managed through Zotero, a widely used bibliography manager in the academic community. Rigorous exclusion and inclusion criteria were applied to select specific studies relevant to the object of study. The study initially analyzed over 47,000 studies on red algae and their applications in biotechnological industry, but only 23 were considered relevant after careful screening. The diversity of red algae species explored in the studies reflects their potential in several research areas such as health, agriculture, and the environment. *Gracilaria* sp. emerged as a prominent species, especially in agar production. Bibliometric analysis revealed a predominance of high-quality studies in high-impact journals, mainly related to the antioxidant activity of algae. However, significant gaps were identified in areas such as cosmetics, genetics, and energy production, suggesting opportunities for future research and development. Based on the conducted study, it is evident that red algae offer a diversified range of biotechnological and industrial applications, with opportunities for exploration in environmental, health, and agricultural sectors. Although some fields are not yet widely disseminated, the collected data provide guidance to direct future research and practical applications, promoting significant advances in the field of biotechnology.

Keywords: macroalgae; Rhodophyta; biotechnology; antioxidant activity.

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Introduction

Algae constitute the primary producers of the planet, characterized by their abundant biomass and morphological diversity, as well as their ability to synthesize a wide range of metabolites with significant economic potential. Primarily found in the marine ecosystem, these organisms play fundamental roles in terms of ecological, evolutionary, and economic importance (Minhas, Kaur, & Kaur, 2020). Algae are generally divided into microalgae, visible through magnification equipment, and macroalgae, visible to the bare eyes (Pereira, 2021). In the categorized context, macroalgae are composed of three distinct groups: Chlorophytes, Phaeophytes, and Rhodophytes, where the relevance of red algae, belonging to the division Rhodophyta, can be highlighted, constituting a substantial group encompassing approximately 7,000 distinct species (Ismail, Gheda, Abo-Shady, & Abdel-Karim, 2020).

Rhodophytes, also known as red algae, constitute a division characterized by chloroplasts devoid of external endoplasmic reticulum, phycobiliprotein pigments, floridean starch reserve, unstacked thylakoids, and absence of flagella. These organisms predominantly present a marine distribution, with only about 3% of the over 5,000 species occurring in truly freshwater habitats (Sheath & Wehr, 2015).

However, the increase in global temperatures driven by climate change poses a significant threat to marine ecosystems, particularly those that support Rhodophytes. Studies suggest that the warming of ocean waters could lead to the decline and even extinction of species such as red algae, which are highly sensitive to thermal

stress. This potential loss not only jeopardizes marine biodiversity but could also have profound economic impacts due to the biotechnological and industrial significance of Rhodophytes (Bennett et al., 2015; Straub et al., 2019; Kumar et al., 2020; Geppi & Riera, 2022). The interplay between climate change and marine ecosystems must be considered, given the multiple benefits these algae provide for ocean health and the global economy.

Red macroalgae present significant biotechnological potential for the synthesis of various products, whether pharmaceutical, nutraceutical, and/or cosmetic. The use of seaweed as phyto-supplements, employed in soil fertilization, formulation of fertilizers, and in animal feed composition, has recently gained greater importance in several countries. These are pioneers in the development of modern biotechnological techniques, due to their substantial economic relevance (Reddy, Gupta, & Jha, 2010).

Various bioactive compounds have been identified in red algae, including polysaccharides, lipids, polyphenols, steroids, glycosides, flavonoids, tannins, saponins, alkaloids, triterpenoids, anthraquinones, and glycosides. Some of these compounds, such as sulfated polysaccharides and carrageenan, are rich sources of soluble fibers and may exhibit antitumor activities. Additionally, lectin present in red algae has shown pro-healing properties and antiulcerogenic activities. In recent decades, a significant increase has been observed in the biotechnological applications of red algae. Techniques such as callus production, tissue culture, protoplast isolation, and fusion are widely available for practically all commercially valuable red macroalgae species (Aziz et al., 2020).

The broad biological diversity of algae offers opportunities for the production of a wide range of bioproducts capable of adding value, through either natural processes or genetic manipulation. Additionally, microalgae present intrinsic advantages, such as reduced production costs, independence from agricultural lands, and rapid growth capacity in large-scale external systems and photobioreactors (Fabris et al., 2020).

Systematic investigation of the industrial and biotechnological applications of red algae is essential due to the complexity and diversity of these organisms and the growing demand for innovative solutions in various industrial sectors. Identifying knowledge gaps and areas with potential for future applications is paramount to drive innovation and practical application of these biological resources. In this regard, the study's objective was to systematically map and inform the different applications of red algae, as well as to discuss the challenges and opportunities for advancement in this field. It also aims to identify specific knowledge gaps and promising areas to guide future research and practical applications.

Material and methods

Search strategy

The systematic mapping followed the recommendations of the PRISMA flow diagram, as suggested by (Moher, Liberati, Tetzlaff, Altman, & the PRISMA Group, 2009). A survey was conducted from February to April 2024, through searches in four databases: Web of Science, Scielo, ScienceDirect, PubMed, and Scopus, accessed through the Capes Periodicals Portal. Boolean operators were used in the search terms: "Red algae" OR "Rhodophyta" OR "red seaweeds" AND "biotechnology" OR "bioprospecting" OR "algae processing" OR "biotechnological applications" OR "marine biotechnology" AND "Industry". All publications found were managed in a bibliographic collection in Zotero®. Duplicate works were excluded, and subsequently, titles and abstracts were read. Only full articles related to the industrial and biotechnological applications of red algae were selected. Filtering was applied regarding the publication period of the documents based on the last five years (2019 to 2024).

Inclusion and exclusion criteria

Some inclusion criteria were established during the search for studies, among these are: only full articles, studies published within the last five years, studies covering only industrial and biotechnological applications of red algae. Regarding exclusion factors, the following materials were eliminated: book chapters, short communications, technical manuals, as well as grey literature such as conference abstracts and case reports. The selection of studies included an initial screening based on titles and abstracts, followed by a full analysis of the selected articles.

Data analysis

An Excel spreadsheet was created for screening the obtained studies, focusing on the arrangement of data such as: title, authors, year of publication, published journal, searched database, and main study objectives

and results. Tables and graphs were also created in Excel and *Graphpad Prism* 7 for presenting the results, and the data were presented through descriptive analysis.

Results and discussion

The initial search in the Scopus, Web of Science, ScienceDirect, and PubMed databases resulted in a total of 47,526 studies that were potentially relevant to the research on red algae and their application in biotechnological industry. However, it is important to note that the extent of this quantity does not necessarily reflect the growing scientific interest in exploring the biotechnological potential of these marine organisms. After the initial search phase, restrictions were applied regarding the publication year and type of material, aiming to refine the selection of studies. This stage resulted in a reduction in the number of eligible articles. Before implementing specific exclusion criteria, 12,981 studies were identified. The ScienceDirect database presented a higher number of results, totaling 45,796, compared to the other databases, while Scopus was the database with the lowest number of studies obtained initially.

After applying the exclusion criteria, aimed at eliminating articles not directly related to the theme or not meeting the defined objectives, only 124 studies remained as candidates to be considered eligible. During the screening process, only one duplicate study was identified, which was removed to avoid redundancies in the analyzed data. Additionally, a critical and in-depth analysis of the remaining studies revealed that only 23 of them properly fit within the scope and interests of the research in question (Figure 1).

The screening revealed a wide range of studies related to marine biotechnology, encompassing not only algae but also microalgae, bioprospecting, microbiology, fungi, cyanobacteria, brown algae, plants, macroalgae, and morphometric analyses, which were excluded. This diversity reflects the breadth of results that databases offer even when specific descriptors are used, which may have influenced the acquisition of studies from general areas.

Adequate structuring of descriptors is necessary, as even with precise definitions, their application during database research often results in either a scarcity or an excessive amount of information, which is frequently not directly related to the researcher's specific interest. (Nobre, Bernardo, & Jatene, 2004).

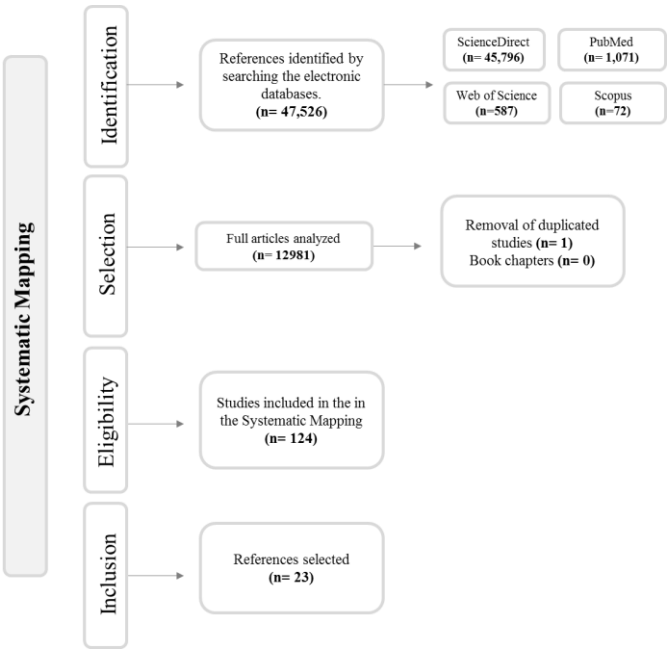

Figure 1. Systematic mapping of biotechnological studies involving red algae, PRISMA flow diagram (Moher et al., 2009).

Based on a qualitative synthesis conducted upon obtaining the selected references, a wide diversity of red algae species explored in the studies was observed, including *Lithothamnium* sp., *Jania rubens, Chondrus crispus, Pterocladia capillacea*, among others. This highlights a biological richness and the potential application of these organisms in various research areas. The functionality of the investigated red algae is varied, ranging from antioxidant properties to applications in bioremediation, showing the versatility of these organisms and their potential in a wide range of scientific and industrial fields. The studies were published

with variation across scientific databases, indicating a widespread dissemination of results and potential collaborations among researchers from different institutions and countries. There was variation in distribution over the period from 2019 to 2024. The authors of the studies represent a diversity of researchers, with individual contributions. This diversity of authors suggests a collaborative and multidisciplinary approach in research on these organisms. It is noticeable that the results presented by the studies emphasize their applicability, satisfactoriness, and potential for present and future uses (Table 1).

Table 1. Synthesis of data from studies on rhodophytes in four major scientific databases.

No.	Study	Author	Red alga used	Functionality	Database	Specific results
1	Biofortification and antioxidant improvement of onion bulbs using calcareous algae and storage	Novaski, Mógor, Amatussi, Queiroz, and Mógor (2023)	*Lithothamnium* sp.	Biofertilizer	Web of Science	The benefits with the use of *Lithothamnium* sp. as a biofertilizer were towards the biofortification of organically grown onions, enhancing the acquisition of mineral nutrients, followed by improvement of antioxidant capacity.
2	Comparative assessment of antioxidant activity and biochemical composition of four seaweeds, Rocky Bay of Abu Qir in Alexandria, Egypt	El-Sheekh, EL-Shenody, Bases, and EL Shafay (2021)	*Jania rubens and Corallina elongata*	Antioxidant activity	Web of Science	These seaweeds, extracted using traditional extraction methods, exhibited high antioxidant activities with significant biomedical, pharmaceutical, and nutraceutical applications. The in vitro antioxidant activities of different solvents of these seaweeds showed dose dependency.
3	Effects of Dietary Supplementation with Red Algae Powder (*Chondrus crispus*) on Growth Performance, Carcass Traits, Lymphoid Organ Weights and Intestinal pH in Broilers	Martínez, Ayala, Hurtado, Más, and Rodríguez (2019)	*Chondrus crispus*	Dietary supplementation	Web of Science	Dietary supplementation with 0.30% red algae improved growth performance (at 21 days) and some edible parts; furthermore, dietary supplementation of 0.40% increased the relative weight of lymphoid organs without altering the intestinal pH of broiler chickens.
4	*Dichotomaria marginata* (Rhodophyta) as a bioindicator for marine pollution: An overview about its metabolites and adsorbed pollutants.	Garcia et al. (2020)	*Dichotomaria marginata*	Bioindicators of marine pollution	Web of Science	The red alga *Dichotomaria marginata* can be a reliable bioindicator of water pollution. Early detection and subsequent remediation will minimize the harmful effects associated with these pollutants and benefit the human population in general.
5	In vitro potential activity of some seaweeds as antioxidants and inhibitors of diabetic enzymes	Ismail, Gheda, Abo-Shady, and Abdel-Karim (2020)	*Pterocladia capillacea*	Antioxidant activity	Web of Science	Besides a wide variation in their antioxidant potential, the seaweeds also exhibited potent in vitro inhibitory activity on α-amylase and α-glucosidase starch hydrolyzing enzymes.
6	Antihyperglycemic and antioxidant activities of a lectin from the marine red algae, *Bryothamnion seaforthii*, in rats with streptozotocin-induced diabetes	Alves et al. (2020)	*Bryothamnion seaforthii*	Antihyperglycemic and antioxidant activities	ScienceDirect	Lectin isolated from the marine red algae *B. seaforthi* showed anti-hyperglycemic activity, also significantly active during insulin production through pancreatic β cells, with a decrease in established insulin resistance through HOMA methods in diabetic rats.
7	Antioxidant and anti-photoaging properties of red marine macroalgae: Screening of bioactive molecules for cosmeceutical applications	Moreira et al. (2022)	*Phycocalidia acanthophora, Porphyra linearis, Condracanhus teedei, Gracilaria cornea, Osmundea pinnatifidae, Plocamium cartilagineum*	Antioxidant activity	ScienceDirect	The potential of red macroalgae as a source of bioactive compounds with anti-aging potential is reinforced.

8	Antioxidant capacity and prebiotic effects of *Gracilaria neoagaro* oligosaccharides prepared by agarase hydrolysis	Zhang et al. (2019)	*Gracilaria neoagaro*	Antioxidant capacity and prebiotic effects	ScienceDirect	The antioxidant capacity and prebiotic effect of NAOSs were also investigated. The results showed that NAOSs exhibited a certain antioxidant capacity.
9	Antioxidant neoagaro oligosaccharides (NAOs) and dietary fiber production from red algae *Gracilariopsis lemaneiformis* using enzyme assisted one-step process	Song et al. (2022)	*Gracilariopsis lemaneiformis*	Antioxidant activity and dietary fiber	ScienceDirect	An enzyme-assisted one-step process could effectively convert homogenized red algae *G. lemaneiformis* into NAOs with antioxidant activity and concentrated dietary fiber with physicochemical properties.
10	Bioactivities of algicidal C18 hydroxy unsaturated fatty acid isolated from the red alga *Tricleocarpa jejuensis* and its synthesized propargylic derivative	Zha et al. (2020)	*Tricleocarpa jejuensis*	Bioactivity	ScienceDirect	Comparative studies on the bioactivities of C18 hydroxy unsaturated fatty acid (Compound A) and its synthesized propargylic derivative (Compound B) revealed that Compound B was much stronger than Compound A in terms of algicidal, tumor cell destruction, and bactericidal activities. This is the first finding that substitution of a double bond in hydroxy unsaturated fatty acids with a triple bond can result in a significant increase in multiple bioactivities.
11	Bioremediation potential of macroalgae *Gracilaria edulis and Gracilaria changii* co-cultured with shrimp wastewater in an outdoor water recirculation system	Mawi, Krishnan, Din, Arumugam, and Chelliapan (2020)	*Gracilaria edulis and Gracilaria changii*	Bioremediation	ScienceDirect	The potential of species *G. edulis* and *G. changii* was studied, and both showed remarkable potential as biofilters in shrimp wastewater. Both macroalgae proved to be a significant positive response to the increasing amounts of ammonia, phosphate, and nitrate in the wastewater medium.
12	Toxicological screening of marine red algae *Champia parvula (C. Agardh)* against the dengue mosquito vector *Aedes aegypti* (Linn.) and its non-toxicity against three beneficial aquatic predators	Yogarajalakshmi et al. (2020)	*Champia parvula*	Larvicidal activity	ScienceDirect	Non-target toxicity of Ex-Cp against beneficial mosquito predators showed lower toxicity at the maximum dosage of 600 ppm compared to Temephos. Thus, the present research provides both target and non-target toxicity of the red algae *C. parvula* against the dengue vector mosquito.
13	In vitro antioxidant study of polyphenol from red seaweeds dichotomously branched gracilaria *Gracilaria edulis* and robust sea moss *Hypnea valentiae*	Mahendran, Maheswari, Sasikala, Rubika, and Pandiarajan (2021)	*Gracilaria edulis*	Antioxidant activity	ScienceDirect	Red seaweeds act as reservoirs of various biologically active substances. The polyphenol compound from red seaweeds carries along potential actives, as it may have strong pharmaceutical value in the future. Additionally, the cultivation of these red seaweeds will draw attention from the small-scale sector, through which pharmaceutical companies gain the true value of *G. edulis*, and a prolific product may reach humanity soon.
14	In vitro human fecal fermentation of agaro oligosaccharides from *Gracilaria fisheri*	Putri, Youravong, and Wichienchot (2022)	*Gracilaria fisheri*	Prebiotic effect	ScienceDirect	The prebiotic index of the seaweed extract was 0.07 and increased to 0.16 and 0.12 with treatments AOS-A and AOS-E, respectively. The production of SCFAs gradually increased during AOS-E

						fermentation, with acetic, propionic, and butyric acids presenting the highest concentrations of 29.75 ± 0.68, 25.95 ± 0.48, and 23.05 ± 0.15 mM, respectively, at 48 h of fermentation.
15	In vitro investigation of silver nanoparticles synthesized using *Gracilaria veruccosa* – A seaweed against multidrug resistant Staphylococcus aureus	Shanmuganathan et al. (2023)	*Gracilaria veruccosa*	Antimicrobial activity	ScienceDirect	Multidrug-resistant bacteria require alternative sources of antimicrobial drugs to combat antimicrobial resistance. Based on the results, the green synthesis of AgNPs using *G. veruccosa* extract may be an effective, inexpensive, environmentally friendly, and safe way to synthesize nanoparticles with microbial activity.
16	Insights into the volatile profile of a red macroalga (*Gracilaria vermiculophylla*) for future food applications	Petronilho, Salvador, Silva, Coimbra, and Rocha (2024)	*Gracilaria vermiculophylla*	Food applications	ScienceDirect	The findings of this study contribute to the uptake of seaweed biomass, such as GV, as an ingredient with an improved aroma profile for future food applications.
17	Statistical optimization of textile dye effluent adsorption by *Gracilaria edulis* using Plackett-Burman design and response surface methodology	Venkataraghavan Thiruchelvi, and Sharmila (2020)	*Gracilaria edulis*	Effluent adsorption	ScienceDirect	The maximum desorption of 23% of the adsorbed biomass was obtained at pH 2. Thus, using statistical optimization designs, we can save time and cost.
18	Structural characterization and protective effects of polysaccharide from *Gracilaria lemaneiformis* on LPS-induced injury in IEC-6 cells	Li et al. (2021)	*Gracilaria lemaneiformis*	Protective effects	ScienceDirect	The purified polysaccharide from *G. lemaneiformis* may be a promising candidate for maintaining intestinal health in the food and pharmaceutical industries.
19	Antioxidant properties of different strains of *Kappaphycus alvarezii* (Rhodophyta) farmed on the Brazilian coast	Araújo Nardelli, Fujii, and Chow (2020)	*Kappaphycus alvarezii*	Antioxidant activity	Scopus	It exhibited the highest antioxidant capacity index, suggesting that this strain may be suitable as a natural source of antioxidants. This is the first report evaluating the antioxidant potential of four strains of *K. alvarezii*, supporting the need for further research to identify and select their value as a viable natural antioxidant source.
20	Concise review of industrially important red seaweed *Gracilaria dura* (C. Agardh) J. Agardh	Mantri, Veeragurunthan, Sambhwani, and Anisoddin Kazi (2022)	*Gracilaria dura*	Raw material applications	Scopus	Efforts to domesticate this species in other parts of the world may pave the way for economic development in coastal rural environments due to its ability to produce high-value agar and agarose, which have applications in the pharmaceutical, medical, and biotechnological sectors.
21	Polysaccharides from red seaweeds: Effect of extraction methods on physicochemical characteristics and antioxidant activities	Premarathna et al. (2024)	*Chondrus crispus, Ahnfeltiopsis devoniensis, Sarcodiotheca gaudichaudii, and Palmaria palmata*	Antioxidant activity	Scopus	The polysaccharides evaluated in this study offer high potential for applications in the food, pharmaceutical, and biotechnology industries.
22	Potential of tropical macroalgae from French Polynesia for biotechnological applications	Zubia et al. (2020)	*Amansia rhodantha*	Bioactivity	Scopus	Some seaweeds from French Polynesia have great biotechnological potential for future applications in aquaculture, health, or cosmetic industries.

23	An overview on red algae bioactive compounds and their pharmaceutical applications	Aziz et al. (2020)	*Laurencia undulata, Melanothamnus afaqhusainii, and Solieria robust*	Pharmaceutical Applications	PubMed	Biotechnological applications of red algae have been increasing. Polysaccharides derived from red algae are important tools for formulating drug delivery systems via nanotechnology.

The analyzed data indicate that the species *Gracilaria* sp. is the most frequently mentioned, with a total of six occurrences, suggesting a representativeness of this species within the set of red algae species listed. In comparison, the other listed species occurred only once or twice, indicating a lower frequency of occurrence. This highlights the importance and prominent presence of *Gracilaria* sp. among the red algae species mentioned in the study list.

It is evident that the red algae *Gracilaria* substantially contributes to about 66% of the global agar production, a polysaccharide widely employed in various industrial applications. It is plausible to infer that this participation is likely to grow as cultivation efforts of *Gracilaria* expand and new technologies are developed to enhance the gel consistency produced by these algae. Despite more than 150 distinct species of *Gracilaria* being reported in different areas of the globe, the taxonomy of this genus remains in a state of constant evolution, which directly impacts the classification and understanding of the various algae variants. The geographic distribution of *Gracilaria* extensively covers different marine ecosystems around the world, with most recorded species originating from subtropical and tropical waters. (Pereira & Yarish, 2008).

In a more in-depth evaluation of the obtained studies, there was a notable peak in research activity in the year 2020, accounting for a total of 43% of the total (n = 10). This increase can be attributed to a series of factors, such as an increase in research funding and the emergence of new technologies. The years 2019, 2023, and 2024 represented only a fraction of 9% of the total (n = 2), stabilizing this value from one year to the next. The year 2020 exhibited a variability of explored themes ranging from bioremediation to health-related aspects (Figure 2A).

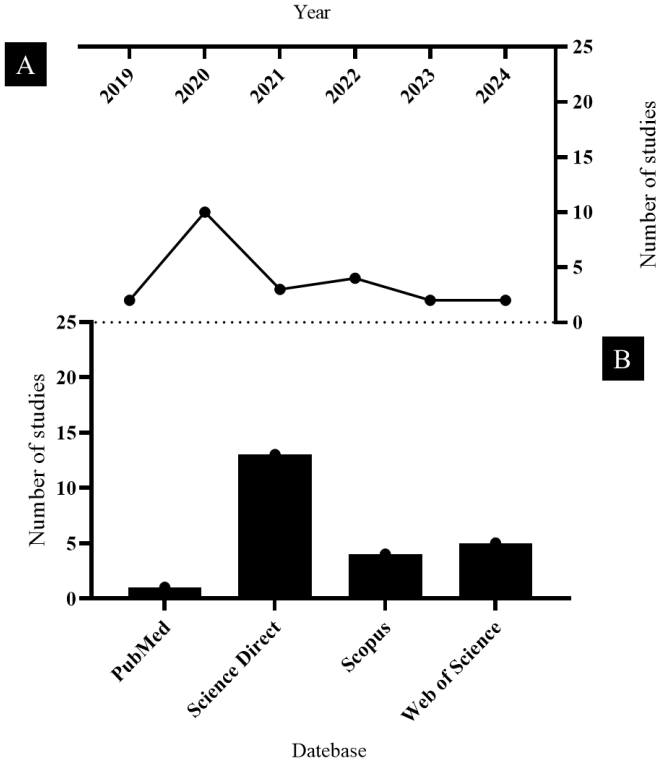

Figure 2. A) Quantitative analysis of the annual distribution of studies on rhodophytes in four scientific databases. B) quantification of studies on rhodophytes in major scientific databases.

The increase in the investigation of studies involving algae in 2020 can be justified by the notable expansion in aquaculture and fisheries production, which recorded a historic record of 214 million tons. This milestone represents a marginal increase of 3% compared to the previous study, which compiled data from 2018, revealing that 178 million tons corresponded to aquatic animals and 36 million tons were algae (FAO, 2022).

Another assessment conducted was regarding the distribution in databases, where initially ScienceDirect and Scopus were the databases with the highest and lowest numbers of results, respectively. After selecting appropriate references within the criteria, it was observed that ScienceDirect remained the database with the highest number of studies, holding 57% (n = 13) of the works, while in this second scenario, PubMed presented only one study after critical analysis (Figure 2B).

The ScienceDirect platform, hosting approximately 25% of the vast corpus of peer-reviewed scientific content globally, stands out for its extensive collection, comprising approximately 12 million scientific articles, 2,200 journals, and 26,000 books. Being of paramount importance in accessing scientific information, ScienceDirect is recognized for its significant contribution to the dissemination of scientific knowledge. It is important to highlight that all data available in the database are indexed in the Scopus database (Louzada-Junior, 2014).

The data analysis revealed a heterogeneous distribution of studies across various research areas. Antioxidant activity was the most represented, with 35% (n = 8) of the studies, reflecting a greater interest in its potential beneficial effects. Studies on bioactivity and raw material applications represented 9% (n = 2) and 4% (n = 1) respectively, suggesting a lesser scale interest in these specific areas. Additionally, health-related issues accounted for around 22% (n = 5) and food and supplementation applications for 13% (n = 3). Meanwhile, the interaction between organisms and their environments received considerable attention, comprising 17% (n = 4) (Figure 3). This distribution of studies highlights the diversity of interests and research areas within the field of microalgae utilization, pointing out the absence of some areas such as genetic engineering.

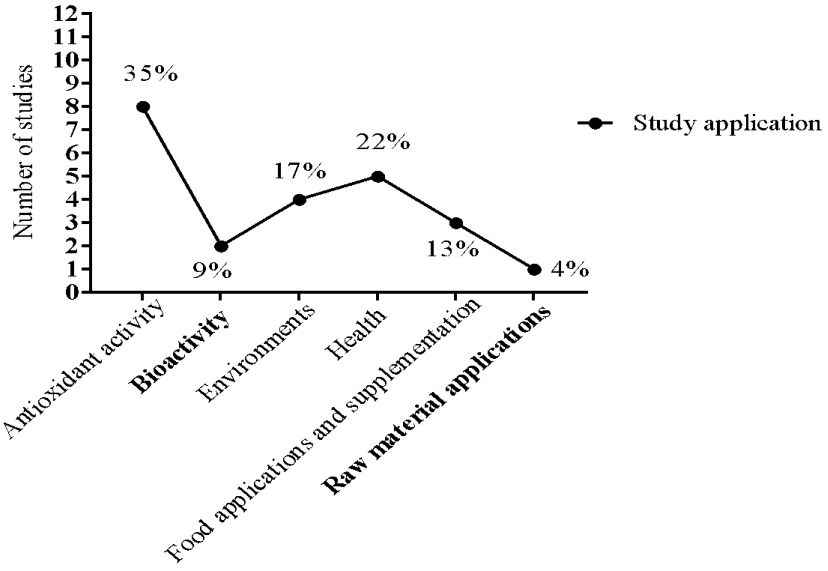

Figure 3. Applications profile of Rhodophytes analysis of the number of studies per utilization area.

Algae and cyanobacteria are recognized as abundant sources of various biologically active compounds, in addition to their nutritional properties. They stand out as one of the primary natural sources of antioxidants and antimicrobial compounds. Their beneficial properties make them valuable resources for food, pharmaceutical, and cosmetic industries. Furthermore, their potential to promote human and animal health is increasingly being recognized and explored (Frazzini et al., 2022).

The antioxidants found in seaweeds play a significant role as "free radical scavengers," mitigating or repairing damage caused by oxidative stress. They exhibit remarkable therapeutic potential for a variety of diseases (Liu & Sun, 2020).

In light of the obtained data, the study also illustrates a bibliometric analysis of scientific articles published in various academic journals, categorized according to the Qualis/Capes stratum. The sample, consisting of 23 articles, was distributed across different strata, indicating a varied distribution of scientific articles in different quality strata, with a significant concentration in stratum A1. The most representative journals in this study include Algal Research, Food Hydrocolloids, and the International Journal of Biological Macromolecules (Table 2).

Table 2. Quantitative analysis in Rhodophytes through the distribution of studies by stratum and journal.

Stratum	Journal title	Total number of articles	Total number of articles (%)
A1	Algal Research	3	13
A1	Aquatic Toxicology	1	4
A1	Bioactive Carbohydrates and Dietary Fiber	1	4
B1	Brazilian Journal of Poultry Science	1	4
A1	Environmental Research	1	4
A3	Environmental Technology & Innovation	1	4
A1	Food Chemistry	1	4
A1	Food Hydrocolloids	2	9
A2	Food Science and Technology	2	9
A4	Heliyon	1	4
A1	International Journal of Biological Macromolecules	2	9
A2	Journal of Applied Phycology	2	9
A3	Phycology	1	4
B1	Revista Ceres	1	4
B3	Revista de biología marina y oceanografía	1	4
B1	Toxicology Reports	1	4
A4	Journal of Complementary and Integrative Medicine	1	4

Within the context of stratification, a significant portion of the studies is concentrated in stratum A1 (48%; n = 11), representing almost half of the total analyzed articles. This suggests a notable predominance of high quality and impactful research within the investigated field, reflecting the recognition and appreciation of these contributions by the academic community. Additionally, strata A2 and A3 (17%; n = 4 and 9%; n = 2) also showed a considerable presence, indicating research of intermediate and moderate quality, contributing to knowledge in their respective areas. Although strata A4, B1, and B3 (9%; n = 2, 13%; n = 3, and 4%; n = 1) represent a smaller proportion compared to the higher strata, they still play a significant role in disseminating research and enriching the body of scientific knowledge (Figure 4). It is also observed that in stratum A1, many of the studies were related to antioxidant activity. The prevalence of studies related to antioxidant activity in high-impact journals such as Algal Research, Food Hydrocolloids, and the International Journal of Biological Macromolecules suggests that this area of research is highly valued and active.

The journals are now subject to a unified evaluation, which combines reach and quality criteria, resulting in eight distinct segments: A1, A2, B1, B2, B3, B4, B5, and C. In this system, journals receive classifications ranging from A1, indicating the highest quality, to B5, representing a lower evaluation (Rosa & Alves, 2011). Therefore, the studies obtained in the mapping fit into the category of high quality and a higher impact factor.

The analysis of the studies reviewed provides a comprehensive understanding of the numerous applications of red algae in scientific and industrial fields. However, it is important to emphasize that red algae can be impacted by specific vulnerabilities. These may include the absence of flagella at any life stage (Oliveira, 2003; Sheath, 2003), their dependence on benthic habitats requiring low turbidity waters, as well altered turbidity affects macroalgal assemblages in coastal waters, increasingly threatened by reduced light availability (Tait, Hawes, & Schiel, 2014), and the large-scale commercial extraction of substances such as agar and carrageenan (Vidotti & Rollemberg, 2004; Bindu & Levine, 2011).

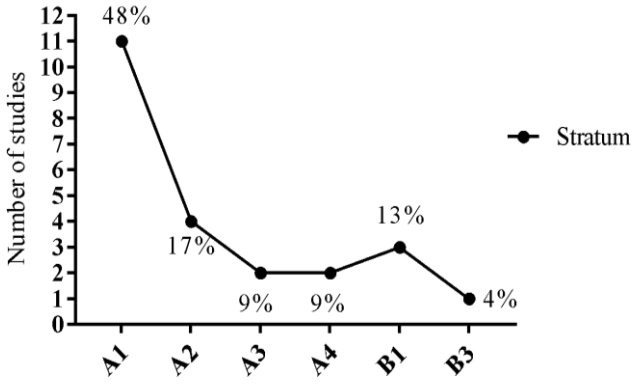

Figure 4. Distribution of studies by stratum.

Such factors not only increase pressure on natural populations but also reduce their capacity to adapt to climate change. The emerging responses of vulnerable species to global changes may vary depending on the quality and availability of resources supporting their productivity under heightened environmental stress (Bell et al., 2022). Therefore, recognizing these vulnerabilities is essential for developing conservation strategies that enhance the resilience of red algae populations to environmental changes and ensure their sustainable use in biotechnological applications.

Given the critical importance of preserving these algae, the findings from this analysis offer a robust foundation for exploring their diverse applications and potential benefits. For instance, Novaski et al. (2023) emphasized the effective use of *Lithothamnium* sp. as a biofertilizer for promoting onion biofortification, resulting in a significant increase in antioxidant capacity and absorption of essential mineral nutrients. This highlights the importance of using red algae in sustainable agriculture but also suggests possible contributions to food security and human health.

At the same time, as an example of contribution to health and biotechnological perspectives, it is possible to highlight research such as that developed by the Federal Universities of Ceará and Pernambuco. These institutions approved a project focused on the extraction and nanoencapsulation of a fluorescent protein from *Solieria filiformis* for use as a biomarker in cancer cells, as well as the development of a polysaccharide for the production of dressings. In addition to other applications of R-phycoerythrin (a phycobiliprotein obtained from algae) also explored by researchers at the Federal University of Ceará, which in particular has expanded research into red algae in Brazil, contributing to these biotechnological advances (Mesquita et al., 2021; Aguiar, Araújo, Martins, Silva, & Silva, 2023a; Aguiar et al., 2023b; Pereira Martins et al., 2023; Sousa et al., 2024; 2025).

Additionally, in a comparative evaluation of the antioxidant activity of *Jania rubens* and *Corallina elongata* algae, remarkable properties were revealed, with substantial biomedical and pharmaceutical implications. The presence of high antioxidant activities in these algae, obtained through traditional extraction methods, suggests vast potential for the development of innovative nutraceutical and medicinal products (El-Sheekh, EL-Shenody, Bases, & EL Shafay, 2021).

In the context of animal nutrition, dietary supplementation with red algae powder (*Chondrus crispus*) has been shown to have beneficial effects on growth performance and the weight of lymphoid organs in broiler chickens. The discovery not only indicates the feasibility of using red algae in animal production but also suggests potential implications for improving productive efficiency and nutritional quality of animal products (Martínez et al., 2019).

Furthermore, studies on the antidiabetic and antioxidant properties of a lectin extracted from the algae *Bryothamnion seaforthii* have also been noted in the studies, offering perspectives for the development of alternative therapies for diabetes. The identification of these bioactive properties can expand the knowledge about the health benefits of red algae, enabling promising therapeutic applications (Alves et al., 2020).

Additionally, research on the ability of the algae *Dichotomaria marginata* as a bioindicator of marine pollution highlights its effectiveness in early detection of environmental contaminants. This aptitude potentially allows for rapid and effective mitigation of the negative impacts on marine pollution, underscoring the crucial role of red algae in environmental conservation and management (Garcia et al., 2020).

Another noteworthy study is the screening of bioactive molecules from red marine macroalgae with great potential in the production of anti-aging compounds. This could have applicability in the health and aesthetics scenario, with red algae serving as sources of natural and sustainable ingredients (Song et al., 2022).

The textile industry was also highlighted among the selected references, enabling the treatment of its effluents, which are often seen as latent problems due to their often-costly disposal. The use of alternative and sustainable methods fits as promising, leading to cost reduction and responsible practices (Venkataraghavan et al., 2020).

The majority of studies addressed the theme of antioxidant activity of red algae, as seen in the studies by Araújo et al. (2020), El-Sheekh et al. (2021), Mahendran et al. (2021), Zhang et al. (2019), Song et al. (2022), and Ismail et al. (2020), which highlights their efficacy in this aspect, as mentioned earlier. The absence of studies in the areas of cosmetics, genetics, energy production and textiles, highlighted significant gaps in current knowledge about the applications of red algae. This absence represents an opportunity for future research explorations, providing a space for innovative investigations and scientific discoveries that can explore and harness the full potential of these organisms in specific fields. Furthermore, exploring the antioxidant properties for the development of cosmetics, moisturizers, and anti-aging products from red algae, could lead to the development of more effective and sustainable products.

Another field where no studies were reported is genetics, indicating a lack of knowledge about the potential of red algae for applications in genetic engineering, such as proteomic and transcriptomic applications. Studying the genomics and molecular biology of red algae could reveal mapping or applicability around their genetic diversity, metabolism, and adaptive potential, enabling applications in areas such as medicine, agriculture, and conservation. In the field of energy production, no studies were obtained regarding renewable biomass sources and biofuels. Investigating the technical, economic, and environmental feasibility of producing biogas, bioethanol, and biofuels from red algae could significantly contribute to the transition to cleaner and more sustainable energy sources.

The systematic analysis of the applications of red algae in the biotechnological industry highlights challenges in filtering a large number of studies due to the diversity of studies and the scope covered by the databases. The wide variety of potential applications of red algae in various sectors, including food, health, and agriculture, stands out as a significant opportunity to explore the potential of these organisms. Specifically, the antioxidant and bioactive properties of red algae make them valuable resources for the development of innovative products and technologies in a variety of areas, representing a potential source of biologically active and sustainable materials.

Despite the opportunities offered by the study of red algae, significant knowledge gaps persist. The absence of studies in specific areas such as cosmetics, genetics, and energy production underscore the need to explore new frontiers of research to unlock the full potential of these organisms. In summary, the analysis of the applications of red algae in the biotechnological industry reveals a complex and multifaceted landscape, characterized by challenges, opportunities, and gaps. Addressing these aspects in a holistic and integrative way is crucial to advancing our understanding of the potential of these organisms and fully exploring their applications in a variety of scientific and industrial fields.

Conclusion

The study provides a systematic overview of the applications of red algae, mapping their potential. By examining various studies, promising opportunities and knowledge gaps that guide progress were identified. Red algae are valuable resources in food, textiles, environment, health, and agriculture. Their diversity and functionality offer numerous possibilities for sustainable innovation. However, gaps exist, particularly in cosmetics, genetics, and energy production, presenting opportunities for research and practical applications that benefit society and the environment. This analysis highlights the applications of red algae and encourages future research, contributing to advances in biotechnology and understanding their potential in scientific and industrial contexts.

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