Discover Agriculture

Review

Agriculture application, comparison, and functional association between macrophytes and microalgae: a review

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Abstract
Aquatic ecosystems are influenced by complex interactions among co-occurring species, impacting energy transfer and ecosystem functionality. Microalgae and macrophytes, as primary producers, play vital roles in regulating water quality, reducing the effects of high temperatures through shading, and contributing to nutrient cycling. Both organisms show significant potential for sustainable applications, including bioenergy production, fertilizers, and bioremediation of wastewater. While microalgae have been extensively studied for their biotechnological applications, macrophytes have received less attention despite their comparable efficiency in nutrient removal and biomass production. This review compares the properties of microalgae and macrophytes in terms of productivity, bioremediation efficiency, and growth-stimulating effects. It also explores potential functional associations between these two groups, highlighting their combined benefits in nutrient recovery, wastewater treatment, and climate change mitigation. The integration of these organisms in agriculture and environmental management offers promising solutions for sustainable resource use and ecosystem health.

Keywords Aquatic photosynthetic organism · Biomass · Bio-stimulants · Nutrition · Organic matter · Phytoremediation

1 Introduction

The intensification of agriculture, driven by the need to meet the increasing global demand for food, has led to significant environmental impacts. In response, sustainable agricultural practices, such as organic and regenerative agriculture, are gaining attention as alternatives to conventional farming. Regenerative agriculture focuses on enhancing soil health, biodiversity, and ecosystem services, including the recovery of organic matter and the improvement of water and nutrient cycles [1, 2].

In this context, microalgae and macrophytes are both photosynthetic organisms with significant potential for agricultural applications. Microalgae are microscopic, unicellular organisms found in various ecosystems, including both aquatic and terrestrial environments [3, 4]. In contrast, macrophytes are larger, multicellular plants that grow in aquatic environments, contributing similarly to nutrient cycling and water quality management [5]. Both microalgae and macrophytes are increasingly recognized for their agricultural benefits, offering sustainable alternatives to conventional farming practice [6, 7].

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The use of microalgae and macrophytes as biofertilizers offers a sustainable alternative for enhancing soil health and reducing the carbon footprint of agriculture [8, 9]. Traditional chemical fertilizers, particularly those containing nitrogen, phosphorus, and potassium (NPK), have long been used to increase agricultural productivity but can contribute to environmental issues, including water pollution and soil degradation [10]. A substantial portion of these nutrients remains unabsorbed by plants, can leading to accumulation in the soil or leaching into water bodies, where they cause eutrophication [11].

In contrast, microalgae and macrophytes can reduce dependency on synthetic fertilizers through their natural ability to fix atmospheric nitrogen and mobilize phosphorus, which reduces the environmental impact associated with conventional fertilizers [12, 13]. Agricultural runoff, a major contributor to water body contamination, exacerbates eutrophication, promoting harmful algal blooms and creating oxygen-depleted dead zones. By absorbing and recycling excess nutrients, microalgae and macrophytes help mitigate these adverse effects [14].

These aquatic organisms are particularly valuable in wastewater management practices, where they can capture nutrients before they enter natural water systems. When integrated into agricultural systems, microalgae and macrophytes not only recycle nutrients but also enhance soil fertility and support sustainable farming practices [7, 15]. Microalgae, with their high nutritional content, act as biostimulants, promoting plant growth and resilience under stress, while macrophytes efficiently remove nutrients from contaminated water sources and can be repurposed as organic fertilizers or compost [16, 17]. Together, they provide an integrated approach to improving soil health, increasing crop productivity, and reducing the environmental impact of agriculture [16, 17].

Microalgal biostimulants have demonstrated positive effects on crop growth and yield, although their widespread commercial use is limited by high production costs and the need for further research [18]. In contrast, macrophytes, which can grow rapidly in non-optimized conditions, demonstrate efficiency in nutrient removal and biomass production, often surpassing microalgae in these areas [19]. The integration of microalgae and macrophytes into agricultural systems has been explored to optimize nutrient recovery, improve wastewater treatment, and enhance resource efficiency [20, 21]. These benefits result from their different mechanisms of action and are influenced by factors such as nutrient availability, temperature, and light conditions [22, 23].

This review aims to offer a detailed comparison of the bioremediation properties of microalgae and macrophytes, focusing on their capacity to treat wastewater, their stimulatory effects on plant growth, and the biochemical composition of their biomass. Additionally, it explores the potential functional associations between these two types of aquatic organisms, highlighting their complementary roles in sustainable agricultural practices.

1.1 Functional characteristics and applications of microalgae

Microalgae are unicellular microorganisms, present in topsoil and aquatic ecosystems and are divided into two groups: chlorophytes and charophytes [24, 25]. They have a complex metabolism that uses processes such as nitrogen fixation and respiration to maintain their structure. Due to these characteristics, some microalgae do not have a restrictive habitat, seeing that they can adapt to various ecosystems [25] colonizing a far greater space than terrestrial plants and consequently being responsible for approximately 40% of the oxygen in the atmosphere [26].

Microalgae can be grown in four major types of cultivation conditions: heterotrophic, photoautotrophic, mixotrophic and photoheterotrophic [27, 28]. Heterotrophic, cultivation as when the algae use organic carbon as both the energy and carbon sources, whereas photoautotrophic use light as an energy source, and inorganic carbon (CO_2) as a carbon source through photosynthesis [29]. Mixotrophic is a combination of both heterotrophic and photoautotrophic cultivation. In photoheterotrophic cultivation conditions, microalgae require light when using organic compounds as the carbon source [28], Despite this, the growth also depends on nutrients and micronutrients such as nitrogen, being the most used type of cultivation [27].

Among microalgae species currently used for commercial purposes, we highlight the *Chlamydomonas reinhardtii* and *Chlorella vulgaris*. *Chlamydomonas reinhardtii* was found suitable for genetic studies in the early twentieth century [30] and has become the model organism for studies of many cellular functions, such as investigating biological processes in photosynthetic eukaryotes [31]. It is also generally regarded as safe (GRAS) which means that it is approved by the FDA (Food and Drug Administration) and considered safe under the conditions of its intended use [32]. Although, clonal reproduction is the most common type, in large population the sexual reproduction of *Chlamydomonas reinhardtii* can possibly increase its adaptation rate to different environmental conditions [33].

Chlorella vulgaris [34] was discovered in the 1890 s by Martinus Willem Beijerinck, a botanical and microbiologist [35]. The studies that began in the 1950 s show its nutritional value for the human diet as a food additive or its lipid used for functional food production [34]. It needs water, CO_2, light and minerals in small amounts to be cultivated and produces a large amount of biomass ranging from 2 to 5 g/L per day in a mixotrophic growth medium [36] in a short time [26].

1.2 Functional characteristics and applications of macrophytes

Aquatic macrophytes are often confused with algae but they belong to the angiosperms that comprise the Anthophyta division [37]. Among the various aquatic plant species, *Azolla*, *Eichhornia*, *Lemna*, *Potamogeton*, *Spirodela*, *Wolffiella*, and *Wolffia* have been most reported as phytotechnology tools in the management of contaminants in aquatic environment [38]. In general, these plants reproduce sexually and asexually, however, asexual reproduction is the most frequent form of propagation [39].

Macrophytes colonize diverse types of aquatic ecosystems, in lakes, reservoirs, wetlands, streams, rivers, marine environments and even rapids and falls. Adaptive strategies are achieved throughout the evolutionary process [40, 41]. These plants are important primary producers in their ecosystems, being relevant eutrophication agents [42]. However, they occur more rapidly in shallow than deep lakes, and the increasing rate of nutrient deposition poses a significant threat to aquatic community structure. Macrophytes play a diverse role in ecological processes (e.g., nutrient cycling), removing heavy metal and other pollutants, maintaining homeostasis in water bodies. Spite of microalgae presents better mobility when the environmental conditions changes are faced, the macrophytes are more able to adapt than microalgae [43]. These fragile vegetables known as the smallest angiosperms in the world, have a vascular system and produce flowers and fruits [44].

2 Carbon sequestration and environmental benefits

Microalgae and macrophytes exhibit exceptional carbon sequestration capabilities due to their high CO_2 assimilation rates in natural aquatic ecosystems [45, 46]. With increasing urgency to reduce carbon emissions and enhance CO_2 capture, these organisms offer significant ecological benefits in mitigating greenhouse gas levels [24]. While croplands can function as carbon sinks, absorbing approximately 0.8 Mg CO_2/ha/year, their terrestrial carbon stocks are severely depleted, leading to negative impacts on soil health [47]. In contrast, microalgae have the potential to sequester up to 6.3 t CO_2/ha/year, with bioactive façade systems capable of capturing up to 99 kg CO_2/m^2 [48], while macrophytes can neutralize 8.5 t CO_2/ha/year [46].

Both microalgae and macrophytes offer more economical and environmentally friendly alternatives for CO_2 sequestration compared to traditional methods. Beyond their carbon uptake, these organisms provide additional ecological benefits by supplementing organic carbon to soil and water even after death and decomposition, contributing positively to the ecosystem [47]. Their nutrient-rich biomass can also be applied for land use management and watershed restoration, offering multiple opportunities for sustainable practices (Fig. 1).

Historically, research has largely focused on microalgae, with macrophytes receiving less attention due to the limited presence of these superior plants in aquatic research sites prior to the 1960 s [38]. However, new innovations and engineered traits offer the potential to develop a range of novel products from these aquatic species, including human food, biofuels, household goods, textiles, and biofaçades powered by both microalgae and macrophytes [48].

Macrophytes systems demonstrate significant potential for CO_2 sequestration and sustainable wastewater treatment. The CO_2 fixation rates (19,592–42,052 mg CO_2/m/d) were approximately three times higher than the emission rates (3048–6017 mg CO_2/m/d), effectively acting as a carbon basin. Furthermore, no methane emissions (< 0.1%) were detected, attributed to low organic loading and redox conditions unfavorable for methanogenesis. In addition, these systems achieved high nutrient removal efficiencies, with reductions of 79% in chemical oxygen demand, 93% in total nitrogen, and 84% in total phosphorus, combining effective wastewater polishing with a net positive environmental impact [49].

3 Agricultural applications of microalgae and macrophytes

3.1 Bioremediation

Aquaculture wastewater treatment systems using photosynthetic organism production are designed to solve environmental and sanitary problems and wastewater-borne nutrients are converted into biomass protein, especially by microalgae and macrophytes [50]. The efficiency of nutrient removal for these organisms is mainly affected by characteristics of the wastewater, environmental, temperature and organic loading rate [51].

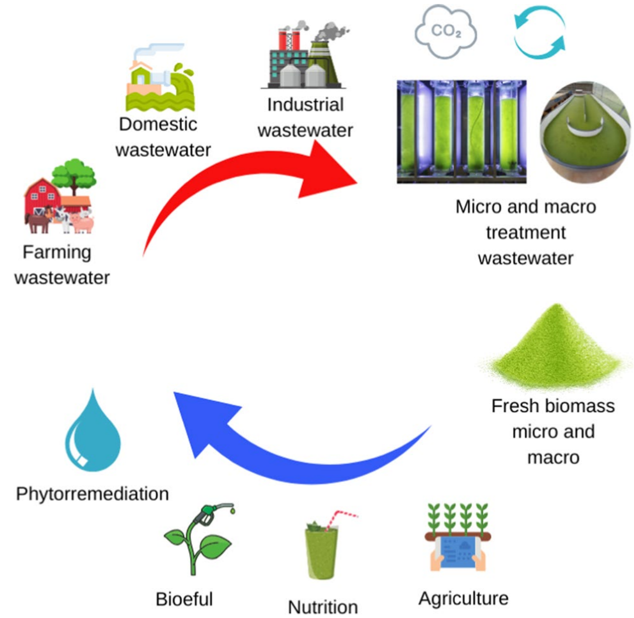

Fig. 1 Flowchart of microalgae and macrophytes wastewater treatment, carbon capture and biomass application. Both the two aquatic organisms can grow on industrial wastewater and used for feed or fuel, agriculture and nutrition

Aquatic ecosystems are continuously contaminated because of excessive anthropogenic pressure which alters the life of animals, plants and microorganisms [42]. Among the various contaminants of water, heavy metals and excessive nutrients nitrogen (N) and phosphorus (P) are the common pollutants responsible for eutrophication of aquatic environment [52].

The aquatic elements associated are economical and efficient in wastewater treatment and have been considered an outstanding alternative for the treatment of agricultural, industrial, and urban wastewaters, as shown in Table 1. The combination of aquatic organisms results in a great removal of excessive nutrients especially N and P, reaching about 90% removal with *Chlorella sorokiniana and Lemna minor* [53]. The lowest percentage of P removal was observed in the domestic effluent after combined treatment by microalgae and macrophytes [54]. The integrated system completely eliminated the wastewaters rich in nitrogen as well showed decontamination potential when tested the phytotoxicity effects on the germination and growth inhibition of *Lactuca sativa* [55]. High performance in removing contaminants by microalgae and macrophytes is reported individually. A better understanding and utilization of the synergistic effects between microalgae and macrophytes should be addressed in future research. Challenges for the sequential treatment process in based constructed wetlands with microalgae and macrophytes, must be considered [51]. The wastewater treatment plant of the University was performed using microalgae in combination with constructed wetland in different photoperiod cycles. The 24-h light cycle was the better cycle nutrients removal since photosynthesis performed by microalgae and macrophytes remained active for all the light period [56].

Recent advances in microalgal co-cultivation systems have highlighted their efficiency in nutrient removal from wastewater, offering sustainable solutions for agriculture. Goswami et al. [57] demonstrated the effectiveness of a two-stage sequential cultivation system, employing *Tetraselmis indica* and *Picochlorum* sp., which achieved nutrient removal rates exceeding 90% for total nitrogen (TN) and phosphorus (TP) under optimized hydraulic retention times. This system not only enhanced nutrient recycling but also generated biomass rich in lipids and bioactive compounds, suitable for agricultural applications. Similarly, other studies emphasize the potential of co-cultivation systems to overcome the challenges of monoculture, such as lower resilience to environmental variations and competition with bacteria. Co-cultivation enhances adaptability and nutrient uptake, optimizing the production of high-value biomass while maintaining water quality [58].

3.2 Biostimulant

The biomass of microalgae and macrophytes can be utilized across a range of crop species, serving a critical function in the integrative framework of agricultural systems (Fig. 2). In the context of agriculture, extensive research has been conducted to employ microalgae and macrophytes as biostimulants, supporting sustainable agricultural practices and contributing to the circular economy (Table 2). Notably, microalgae genera such as *Chlorella*, *Chlamydomonas*, and

Scenedesmus are recognized for their ability to synthesize hormone-like substances that enhance plant growth [59]. Similarly, aquatic plants, or macrophytes, including water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), and various species of duckweed (*Spirodela*, *Landoltia*, *Lemna*, *Wolffiella*, and *Wolffia*), perform vital ecological functions and can serve as natural fertilizers. Beyond their environmental benefits, the biomass of these macrophytes regards potential for diverse applications such as animal feed, biofuel production, pellets, and ceramics [60]. The utility of aquatic macrophytes in biofertilizer development and food production has been recognized for decades, as first detailed by Peter Edwards in 1980 [61].

The biostimulant potential of microalgae and macrophytes offers varied benefits to crops, depending on their mode of application. Despite the growing awareness of sustainable agricultural practices, global food production still heavily relies on chemical fertilizers and pesticides [79, 80], the excessive and prolonged use of which has led to significant environmental and health concerns, notably through water pollution [81]. In contrast, the increasing recognition of the need for sustainable agricultural systems that minimize environmental pollution emphasizes the importance of finding eco-friendly alternatives to synthetic fertilizers. The adoption of novel, natural fertilizers such as nano-fertilizers, biodegradable polymers, and biochar has become a key strategy for promoting sustainability. Microalgae and macrophytes offer a natural source of nutrients, reducing the reliance on synthetic fertilizers. Their integration into agricultural systems not only improves soil health but also promotes nutrient cycling, reduces nutrient runoff, especially on sloped soils [82].

The growth medium derived from *Chlorella sorokiniana* was applied to soil with wheat seedlings, resulting in a 30% enhancement in plant growth parameters. Notably, total dry biomass, shoot, and root length increased by 22% and 51%, respectively, compared to the control group. These findings suggest that the extracellular exudates from *C. sorokiniana* contribute positively to plant growth [62]. Additionally, an aqueous microalgae solution significantly promoted the growth of *Medicago truncatula*, with *Chlorella* application yielding more robust plants, greater fresh biomass, larger leaves, and an increased number of flowers/pods compared to both the control and *Chlamydomonas*-treated samples [63].

For *Solanum lycopersicum* (tomato) plants, the application of microalgae and macrophytes as seed primers, biofertilizers, and foliar sprays has been shown to enhance various physiological characteristics, including the number of flowers and branches, weight, germination speed, growth, and yield [65, 66]. In one study, crude polysaccharide extracts from three microalgae strains were applied to tomato plants via irrigation. The carbohydrates, sulfate content, and uronic acids derived from the polysaccharides exhibited a strong correlation with growth stimulation, with growth hormones, such as brassinosteroids, detected in the CG-MS profile [66]. Beyond their role as plant biostimulants, microalgae also show promise as biocontrol agents [67]. The bioactive properties of *Chlorella vulgaris* freeze-dried biomass extract was assessed after storage for 15 months under various conditions (in the dark at − 70 °C, 10 °C, and 25 °C, and in light at 25 °C). The antimicrobial activity of *Chlorella vulgaris* biomass against *Staphylococcus aureus* and *Escherichia coli*, as well as its antioxidant activity, were found to increase over up to 12 months, emphasizing the need to explore the shelf-life of microalgal biostimulants for commercialization [67].

Microalgae also play a significant role in modulating the expression of genes in microorganisms involved in the nitrogen and carbon cycles, thereby enhancing the physico-chemical and biological attributes of the soil, which are beneficial to plant growth [83]. The incorporation of microalgae into soil resulted in increased bacterial diversity, which, in turn, supported the enhanced availability of organic carbon, as well as essential minerals such as N and P. This study highlighted a greater abundance of genes involved in nitrogen cycling pathways, including nitrogen fixation (nifD), nitrification (hao), and denitrification (narG, nirK), in soil treated with microalgae [68]. A similar effect was observed in the strawberry rhizosphere, where microalgae treatment altered the microbiota community structure in the soil, root tissue, and crown tissue. Notably, two specific bacterial genera, *Streptomyces* and *Actinospica*, were identified, and these were linked to heavy metal tolerance through phytoremediation [70].

For *Zea mays* (maize), *Chlamydomonas reinhardtii* and *Chlorella sorokiniana* have proven to be effective biostimulants, mitigating stress-related damage under conditions such as nitrogen (N) deficiency [69]. Maize seedlings were cultivated in hydroponic systems with both low and high nitrogen levels and supplemented with algae biomass. *Chlorella sorokiniana* enhanced secondary root number, root area, volume, and length, while *Chlamydomonas reinhardtii* improved both root and shoot dry mass, along with micronutrient accumulation, thereby increasing the plant's resilience to stress. In response to nitrogen deficiency, *Chlorella sorokiniana* promoted the accumulation of manganese (Mn^{2+}) in both roots and shoots, as well as copper (Cu^{2+}) in the roots, micronutrients that are important for nitrogen metabolism [69]. Under water-stress conditions, foliar irrigation with *Arthrospira platensis* aqueous extract exhibited positive effects on leaf gas exchange, maintaining open stomata without affecting water potential. Consequently, the treated vines exhibited greater berry weight compared to untreated vines [71].

Table 1 Nutrient removal by association of microalgae and duckweeds in different wastewater treatment

Wastewater	Species	Cultivation conditions	Initial (COD; NH_4-N; PO_4-P mg/L)	Time (d)	Removal (%)			References
					COD	NH_4-N	PO_4-P	
Industrial	*Chlorella vulgaris* + *Lemna minuta*	Microalgae were cultivated in a 16.5 L inverted triangular acrylic bioreactor with 5 L of solution and continuous aeration via silicon tubing. Macrophytes were grown in rectangular glass bioreactors with an 18 L capacity, containing 6 L of microalgal-treated wastewater	3,100; 3–8; 1.5–3.5	10	61	71.6	28	[70]
Municipal	*Chlorella sorokiniana* + *Lemna minor*	The sequencing batch reactor system consisted of two reactors operated in series. Reactor 1 (2 L) contained *Chlorella sorokiniana* and was maintained at 24 ± 2 °C, while Reactor 2 (2 L) housed *Lemna minor*, also at 24 ± 2 °C. Filtered municipal wastewater was used with a hydraulic residence time of 3 days. Reactor 1 was inoculated with 800 mL of growing *Chlorella sorokiniana* and Reactor 2 with 4 g of *Lemna minor* biomass. The experiment ran for 30 days under 16 h light/8 h dark conditions. After each cycle, 1500 mL of treated wastewater was transferred from Reactor 1 to Reactor 2 for further treatment	618; 54, 4.2	30	99	90	91	[66]
Palm oil mill	*Chlamydomonas incerta* + *Lemna minor*	Palm oil mill effluent was used as the culture medium for three algae combinations: (1) pure *Lemna minor*, (2) pure *Chlamydomonas incerta*, and (3) a combination of both. The experiment began by inoculating 3000 mg of *Lemna minor* into reactor 1 and 3000 mg of *Chlamydomonas incerta* into reactor 2. In reactor 3, 1500 mg of *Lemna minor* and 1500 mg of *Chlamydomonas incerta* were mixed. Each reactor had a volume of 500 L, containing 200 L of wastewater. All reactors were bubbled with carbon dioxide and air for 14 days under fluorescent light	–	14	4.4	11.3	70.47	[7]
Domestic	*Chlorella sp.* + *Senedesmus sp.* + *Euglena* sp + *Lemna minor*	Duckweed-microalgae constructed wetland operated as a continuous flow system with a hydraulic retention time of 72 h. It was exposed to environmental conditions, with a summer average water temperature of 20.9 ± 3 °C and a winter average of 11.7 ± 1 °C. The system was used for tertiary wastewater treatment following primary clarification and activated sludge processes	210; 55; 12	180	67.5	65.19	21.5	[67]

Table 1 (continued)

Wastewater	Species	Cultivation conditions	Initial (COD; NH_4-N; PO_4-P mg/L)	Time (d)	Removal (%)			References
					COD	NH_4-N	PO_4-P	
Urban	*Pool microalgae* + *Hymenachne grumosa*	An integrate systems combining the sequential use of microalgae (MA) and vertical flow constructed wetland (VFCW) with macrophyte operated in batch modus, with hydraulic retention time (HRT) of 3 days for each unit. The VFCW was fed for 1 h with 90 L of the wastewaters from the anaerobic unit while the MA system was also fed with 90 L every 3 days, wherein the sequential received wastewaters from the pre-treatment with MA after 3 days of recirculating also with supply of the same 90 L of VFCW	526.4; 68.8; 7.71	365	70	100	–	[71]
Wastewater-University	*Nitzschia* sp., *Gomphonema* sp., and *Chlorella* sp. + *Chrysopogon zizanioides*	Three boxes at sequential system were installed in a step-like structure. The first box corresponds to the microalgae tank that receives the effluent from the anaerobic reactor by means of a hydraulic pump. The second box the effluent passes through the sand biofilter and finally through the constructed wetland containing the macrophyte. The effluent had an HRT of 7 d in each system. The microalgae growth efficiency was tested at three different light cycles: 12 h/12 h, 24 h and 18 h/6 h (light/dark), each lasting seven weeks	1088.6; 75.2; 3.5	60	63.7	94.1	60	[56]

COD chemical oxigen demand; NH_3-N: Ammonical Nitrogen, PO_4-P: Phospate

The extract of biomass microalgae cultivated in swine wastewater serves as a liquid fertilizer, effectively promoting the growth of wheat seedlings at concentrations of 1 mg/L and 5 mg/L. Under salt saline stress (100 mM), microalgae extract (1 mg/L) increased the wheat root growth and modulated the antioxidant system and phytohormone content. The results suggested that the application of exogenous phytohormones (GA3, SA, IAA, ABA, and ZT) [72].

Duckweed extracts have also been shown to enhance maize germination, biomass, leaf area, pigment content, and vigor index. *Lemna* aqueous extract positively affected seedling development and increased maize plant biomass, likely due to enhanced nutrient acquisition by the plants under duckweed treatment. Maize samples treated with 0.50% and 1.00% duckweed extract exhibited significantly higher nitrogen content than the control samples. Furthermore, maize samples treated with 0.05%, 0.50%, and 1.00% duckweed extracts contained greater levels of phosphorus, potassium, calcium, and sodium compared to the controls [73]. It is noteworthy that only a few studies in the literature explore duckweed as a source of biostimulant substances.

Vermicompost, a potent fertilizer, is ideal for organic agriculture. The process of vermicomposting involves the bio-oxidation and stabilization of organic material through the combined action of earthworms and microorganisms. Earthworms play an essential role in fragmenting and aerating the substrate, which dramatically alters microbial activity and increases the surface area for microbial colonization [84]. This process improves soil physical properties, increases nutrient availability, and enhances water-holding capacity [85]. Soils fortified with *Azolla* sp. vermicompost exhibited higher growth parameters and yields in *Solanum melongena* L. (eggplant) compared to those treated with *Eichhornia* sp. vermicompost [74]. Similarly, *Salvinia molesta* vermicompost promoted germination and seedling growth in *Vigna radiata* [76]. Vermicompost also supplies additional substances, such as 3-Indole Acetic Acid, a plant growth regulator derived from humic acids produced by earthworms (*Eisenia foetida*), which boosts crop growth and yield [85, 86]. Vermicomposting transforms invasive plant species from harmful agents into sources of soil enrichment by neutralizing their allelopathic effects and releasing beneficial nutrients. In the case of *Salvinia molesta*, the allelopathic chemicals it contains are largely broken down during the composting process, reducing its ecological threat. There is also some indication that part of its lignin is decomposed in the process. The resulting vermicompost has been shown to support seed germination, stimulate plant growth, and improve the soil's physical, chemical, and biological properties [76]. This process also leads to increased nitrate and ammonium concentrations in the soil, along with greater microbial biomass

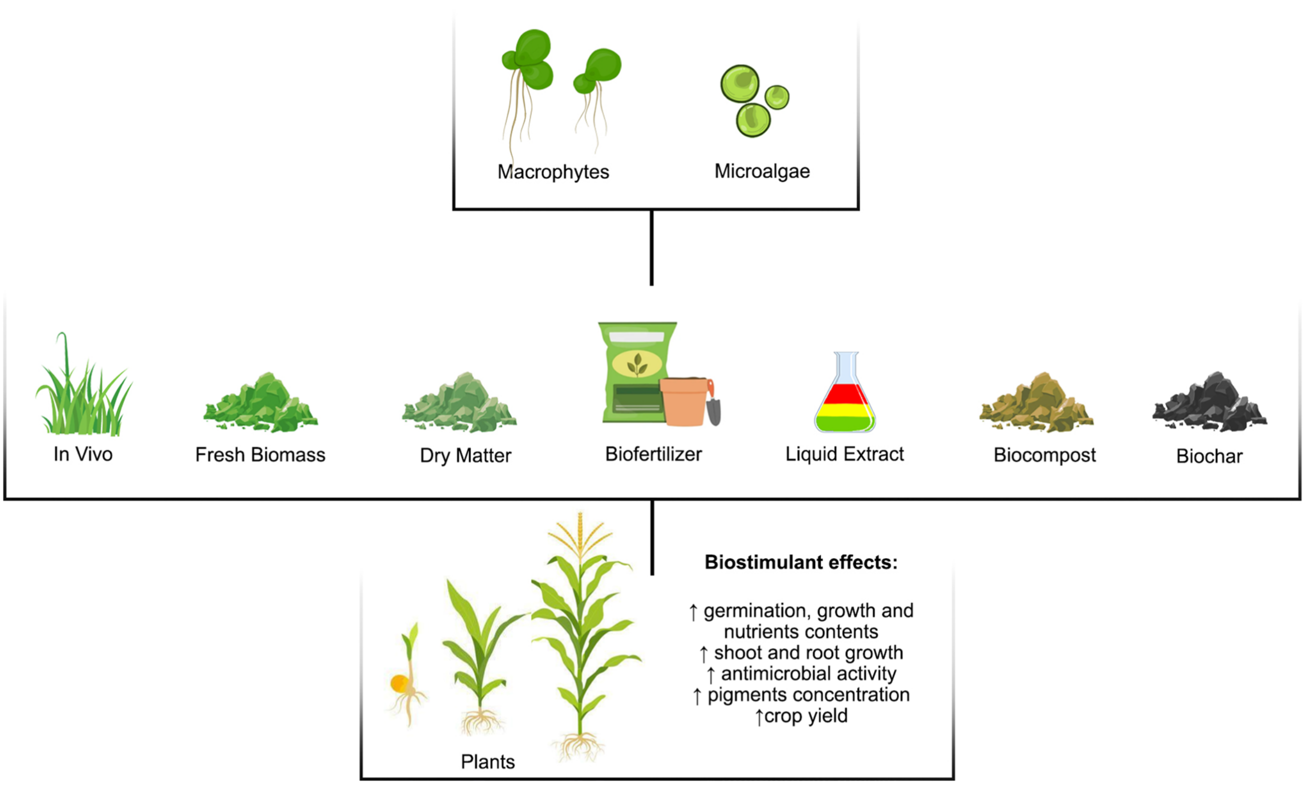

Fig. 2 Agricultural applications of macrophytes and microalgae, detailing their diverse uses and biostimulant effects on plant growth and productivity

Table 2 Biostimulation studies in agriculture from microalgae and macrophytes

Crop	Microalgae	Application method	Biostimulant effect	References
Triticum aestivum	*Chlorella sorokiniana*	Algae aqueous-on soil	↑ plant length	[62]
Medicago truncatula	*Chlorella*, *Chlamydomonas reinhardtii*	Live algae cell-soaking soil	↑ shoot length, fresh weight, pigment content (total chlorophyll, a, b and carotenoids), number of flowers and leaf size	[63]
Solanum lycopersicum	*Arthrospira platensis* *Dunaliella salina* *Phorphoryduym* sp. *Acutodesmus dimorphus* *Chlorella ellipsoidea* *C. pyrenoidosa* *C. vulgaris* *C. sorokiniana* *C. marina* *Scenedesmus dimorphus* *S. obliquus* *Chlamydomonas reinhardtii* *Dunaliella salina* *Tetraselmis marina* *Tetraselmis sp.* *T. suecica* *Porphyridium sp.* *Isochrysis galbana* *Nannochloropsis gaditana* *Aphanothece* sp.	Microalgae polysaccharides- irrigation on soil Extract of cells-sprayed at leaf Crude bio-extracts-applied as soil drench	[a] ↑ nodes number, shoot length, shoot dry weight, protein, carotenoids and chlorophyll contents ↑ nutrient of soil ↑ root growth: 84.80% and 70.88% with *C. pyrenoidosa* and *C. ellipsoidea*, respectively; ↑ shoot growth: 53.6% for *C. ellipsoidea, 45.67%* and *35.18%* for *Porphyridium sp*. and *C. marina,* respectively; ↑ shoot dry weight: 55.66% and 49.60% for *C. ellipsoidea* and *C. pyrenoidosa;* ↑ concentration of photosynthetic pigments (chlorophyll b); ↑ NPK: on root: N- 89.79%, P- 52.15%, and K-78.04%, for *C. ellipsoidea*	[64–66]
Vigna radiata	*Chlorella vulgaris*	Freeze-dried biomass solution	↑ antimicrobial activity (against of *Staphylococcus aureus* and *Escherichia coli*	[67]
Lolium rigidum Gaudin	*Chlorella* sp. *Scenedesmus* sp.	Dried mass- added on soil	↑ root height, fresh weight, and dry weight	[68]
Zea mays	*Chlamydomonas reinhardtii*	Lyophilized powder from intact cells-in hydroponic system	↑ micro-nutrients accumulation on shoots and roots	[69]
	Chlorella sorokiniana		↑ the number of secondary roots	
Strawberry Keumsil	*Scenedesmus sp.*	Cells dilution-100 mL/plant	Development of beneficial plant microbiota communities	[70]
Vitis vinifera	*Arthrospira platensis*	Microalgae extract- foliar application	Better leaf gas exchange and water potential; ↑ weight	[71]
Wheat	*Chlorella sp.*	Microalgae extract	↑ root fresh weight, seedling fresh weight, longest and total seedling length Softened the salt stress	[72]

Table 2 (continued)

Crop	Macrophyte	Application method	Biostimulant effect	References
Zea Mays	*Lemna minor*	Seed germination	↑ biomass ↑ leaf area ↑ vigor index ↑ Macro and micro-nutrients	[73]
Solanum melongena L	*Azolla sp.*	vermicompost (4:1 v/v)	↑ growth and yield	[74]
Raphanus sativus L	*Eichhornia crassipes*	Compost (1:1 v/v)	↑crop yield	[75]
Vigna radiata	*Salvinia molesta*	Vermicompost: 2–20% (w/w)	↑ germination, growth and N contents	[76]
Oryza sativa	*Pistia stratiotes*	compost with soil	↑ plant growth	[77]
Lactuca sativa L	*Lemna minor*	Incorporate with soil (60, 120, and 180 kg ha^{-1} N)	↑ lettuce yeld ↑ number of leaves per plant	[78]

[a] *NPK* Nitrogen (N), phosphorus (P) and potassium (K)

carbon and a more diverse microbial community [76, 77]. Given that some aquatic macrophytes are considered invasive species, their disposal can be mitigated by utilizing them in organic agriculture. The use of aquatic photosynthetic organisms as bio-fertilizers not only provides additional benefits but also helps offset some of the costs associated with mechanical harvesting, resulting in cleaner water bodies [77].

Lemna minor biomass, cultivated in hydroponic synthetic system, when incorporate with soil increased the yield, head diameter, number of leaves, fresh and dry weight in the autumn than in the summer season of lettuce. The better efficiency nitrogen use (NUE) was with lowest level (60 kg h^{-1} N) showed as the most suitable for the fertilization of lettuce and indicating that its biomass as a potential green manure improving the sustainability of horticultural production systems [78].

In fact, alone or synergistically, macrophyte and microalgae can impact much more positive than negative for various crops mainly, to increase the seed germination, root and shoot development and yield by its biostimulant effect (hormones, D-lactic acid) [87, 88]. There are a complex association between macrophytes and microalgae that influence to the ecosystem services like, nutrient retention, decomposition, mineralization, and sedimentation of their biomass on soil and more studies are needed to test this correlation. These aquatic organisms have rapid growth that cause less concern about environmental pollution and can use in sustainable agriculture.

3.3 Biomass biochemical composition

Understanding the nutraceutical properties of microalgae and macrophytes is fundamental for advancing their potential in novel food production and other future applications [60, 89]. Notably, these organisms provide a unique advantage in agricultural contexts, when grown on a large scale in ponds or photobioreactors, are more water-efficient than traditional crops [90, 91]. They can be cultivated on non-arable land with minimal freshwater use, and even in seawater or wastewater.

Table 3 presents a comparative analysis of the nutritional value between microalgae and macrophyte biomass. Nutritionally, a comparable content of carbohydrates, proteins, and ash has been observed across varied species of microalgae. Specifically, *Chlamydomonas reinhardtii* and *Chlorella vulgaris* exhibit similar protein levels, with protein content surpassing their lipid concentrations [31].

The nutrient composition of macrophytes reveals that the genus *Wolffia* surpasses microalgae in both carbohydrate and protein content [94]. However, lipid concentrations in macrophytes are typically lower when cultivated in synthetic growth media [95]. While starch levels are comparable between microalgae and duckweed (*Spirodela, Landoltia, Lemna, Wolffia and Wolffiela*), *Chlorella vulgaris* exhibits a higher starch concentration relative to other species (Table 3). In the case of duckweed, exploring the nutritional value of these plants highlights their potential as an important food source for human nutrition, where the emphasis on nutritional quality often outweighs the pure quantity of specific components [94]. While low starch levels may not pose a significant issue in developing regions where staple foods such as rice and wheat predominate, the higher dietary fiber content of duckweed offers a valuable contribution to improving diets by providing low-energy food options [96].

In several Asian countries, the *Wolffia* is recognized as a significant protein source, locally referred to as "water-eggs" due to its protein content exceeding 25% of dry weight, surpassing the World Health Organization's (WHO) recommendations. Fresh *Wolffia* plants are used in a variety of culinary preparations, including salads, omelets, and vegetable curries [97], and can also be incorporated into bread, pasta, and sports nutrition products. Similarly, microalgae are regarded as "superfoods" and "food crops" because of their excellent nutritional profiles and potential for use in other industries such as biofuels, cosmetics, and pharmaceuticals (such as phenolic compounds) [31, 98]. The advanced development of recombinant protein technology in microalgae further differentiates them from macrophytes. The cultivation of *Chlorella* is well-established and deemed safe for human consumption. However, growth conditions can influence the composition and nutritional identity of microalgae, supporting their characteristics to be adapted to meet specific market demands [99].

Table 3 Nutritional values (%) of microalgae and macrophytes grown in synthetic medium

Specie	Carbohydrates	Protein	Lipid	Ash	Fiber	Starch	References
Chlorella vulgaris	29.3	45.3	16.1	29.3	9.18	14.65	[31, 92]
Chlamydomonas reinhardtii	23.6	46.9	24.7	23.6	–	11.8	[31]
Wolffia brasiliensis	25	23	5,5	190*	9	10–15	[93, 94]
Wolffia arrhiza	31.33	50.89	6.07	11.71	15	11–15	[94, 95]

*g/Kg

4 Challenges and prospects

Microalgae and macrophytes biomass contain high nutrient levels and many studies have shown their effectiveness as resource for reducing the use of chemical fertilizers. Thus, minor adjustments can promote plant growth, increase the yield, improve the microbiota and soil structure and eliminate the excess nutrients/pollutants [9, 18]. In this context, duckweeds can be more explored in agronomic ecosystems.

The microalgae and macrophytes cultivation are not dependent on agricultural land, it can also be installed in hostile environments, including space farming due to the biomass quality with optimal nutrient to sustain the human life [100]. Microalgae with macrophytes alone or acting in synergism could expand the scope of wastewater treatment and increase nutrient removal efficiency. Although the combined systems are economical and easy to be operated, some major challenges still exist such as rigorous management, to promote better development and production, as well as a biological efficient treatment.

Microalgae and duckweeds offer enormous potential for high-quality compounds, some of which are already in use [101]. Nowadays, green factory platforms for recombinant protein production offer the potential for a large-scale and cost-effective expression system. The expression systems encompass diverse forms including whole plants, suspension cells, hairy roots, moss, duckweeds, microalgae [102]. The majority of current work is performed with the well-characterized microalgae *Chlamydomonas reinhardtii* [103]. Recently, from aquatic plants, duckweeds seems ideal to produce recombinant protein, with stable transformation for the genus *Wolffia* [104, 105]. However, the development of economical and viable green biofactory is still not effective with a consistent transformation method for a duckweed, specially. In this way, some difficulties persist over the time such as low recombinant protein yields by microalgae and macrophytes as well as the lack of production systems optimization for large-scale growth and harvesting under photoautotrophic conditions [106]. Intense efforts have been deposited both biological and engineering-based to development and optimization of the photobioreactor culture systems for the success of the bioproduction platform.

In addition, addressing key knowledge gaps is essential for the successful integration of these organisms into large-scale agricultural systems. A major challenge is in the scalability of these systems, particularly in relation to the land area required for cultivation and the variability in nutrient content when utilizing wastewater as a growth medium [107, 108]. Further research is necessary to optimize cultivation methods, including the design of photobioreactors for microalgae and the development of cost-effective harvesting techniques for macrophytes, to improve efficiency and reduce production costs.

To integrate these organisms into modern agriculture, a phased approach is recommended. First, identify the most suitable species based on their nutritional value, adaptability, and potential for nutrient recycling. Second, establish infrastructure and supply chains to ensure a consistent and large-scale production of bio-inputs. Governmental and industrial support is important in this process, as highlighted by Brazil's National Bio-supply Plan (NBP, No. 10.375), which aims to expand bio-input adoption and leverage local biodiversity.

Additionally, interdisciplinary collaboration is essential to address logistical, technical, and regulatory barriers. Pilot projects combining macrophytes and microalgae in wastewater treatment and biofertilizer production can serve as models for large-scale implementation. By prioritizing research and development public–private partnerships, agriculture can transition towards a circular economy, leveraging these organisms to improve resource efficiency, reduce environmental impacts, and enhance productivity in a sustainable manner.

5 Conclusions

Based on a circular economy, microalgae and macrophytes provide advantages in the search for eco-friendly alternatives for the development of sustainable agriculture. On the other hand, regarding duckweed in agricultural biostimulation, further studies are needed, due to the importance of these organisms in the ecological agroindustry. Several studies highlighted the performance of microalgae and macrophytes and showed their potential for recycling biological resources. Together, they demonstrated potential nutrient removal efficiency for different wastewater treatments. Changes to improve the management and association of both green biomasses can optimize nutrient uptake and increase biomass productivity.

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Declarations

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