Microalgae: Potential for Bioeconomy in Food Systems

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Abstract: The efficient use of natural resources is essential for the planet’s sustainability and ensuring food security. Colombia’s large availability of water resources in combination with its climatic characteristics allows for the development of many microalgae species. The use of microalgae can potentially contribute to sustainable production in support of the agri-food sector. The nutritional composition (proteins, carbohydrates, fatty acids, vitamins, pigments, and antioxidants) of microalgae along with the ease of producing high biomass yields make them an excellent choice for human and animal nutrition and agriculture. Several species of microalgae have been studied seeking to develop food supplements for pigs, ruminants, poultry, fish, crustaceans, rabbits, and even bees. Important benefits to animal health, production, and improved bromatological and organoleptic characteristics of milk, meat, and eggs have been observed. Based on the functional properties of some microalgae species, foods and supplements have also been developed for human nutrition. Moreover, because microalgae contain essential nutrients, they can be utilized as biofertilizers by replacing chemical fertilizers, which are detrimental to the environment. In view of the above, the study of microalgae is a promising research area for the development of biotechnology and bioeconomy in Colombia.

Keywords: animal nutrition; biofertilizers; Colombia; functional foods; sustainability

1. Introduction

Colombia has five large continental hydrological zones and numerous rivers, including the Magdalena, Putumayo, and Cauca [1]. Within these zones, six units comprise approximately 1900 swamps and wetlands, of which 80% are located in the Caribbean region [2]. It also has marine and oceanic waters, with two coastlines spanning 1642 km in the Caribbean and 1300 km in the Pacific [3]. The climatic, orographic, and hydrological characteristics allow for the existence of numerous ecosystems and appreciable biodiversity, which makes Colombia a megadiverse country [4]. Together, these natural resources offer the potential for biotechnological development, sustainable use, and growth of the bioeconomy in the country.

Paradoxically, 27% of Colombian ecosystems are at critical risk and 17% are at risk in terms of biodiversity, ecosystem services, and social welfare [5]. In addition, poverty has historically been a social problem, and in the last 10 years, 34.7–42.5% of Colombians have been classified as poor [6]. In this regard, conservation of biodiversity is essential for facing economic, social, and climatic problems.

Bioeconomy integrates science, society, economy, industry, and environment for sustainable development [7]. It aims at satisfying the needs of individuals in the agri-food and energy sectors mainly, in balance with the environment [5]. Since the implementation of the United Nations 2030 Agenda, bioeconomy has been fostered in Latin America as a commitment to sustainable development [9]. In Colombia, the green growth policy focuses on technological development and boosting economic productivity on the basis of environmental sustainability and social inclusion [10].

Microalgae are aquatic microorganisms [11] that are an important source of biomass in food chains [11–13]. These microorganisms contain chloroplasts or photosynthetic cell
structures, and phycobiliproteins such as chlorophylls and carotenoids [11,14,15]. The estimated number of microalgal species ranges from 200,000 to several million [11,16]. Many species are used in agriculture, food, bioremediation, biological control, CO₂ fixation, and alternative energy production [17–20].

Microalgae are widely distributed in a variety of aquatic and terrestrial environments; they are part of the plankton and play a major role in ecosystems. Approximately half of the planet’s photosynthesis and oxygen production can be attributed to microalgae, which makes them essential for carbon fixation [12,13,21].

Considering the abundance of hydric resources and ecosystems, a high diversity of microalgae is expected in Colombia. Nevertheless, microalgae and their applications have been poorly studied in the country. Therefore, there is considerable potential in Colombia for the development of biotechnology and bioeconomy using microalgae, which are necessary for agri-food security. This review discusses some applications of microalgae biomass that could be developed in Colombia.

2. Biodiversity

Microalgae are a highly diverse group that includes prokaryotes (cyanobacteria) and photosynthetic eukaryotes belonging to three kingdoms: Protozoa, Chromista, and Plantae [11,22]. The classification of microalgae has been based on morphological, physiological, and ecological features. Recently, molecular and ultrastructural characteristics have been included in this classification [23]. Due to the differences between the classification systems for prokaryotes (International Code of Nomenclature of Prokaryotes) and those for eukaryotes, such as the International Code of Nomenclature for algae, fungi and plants, many authors exclude cyanobacteria from the microalgae group. Nevertheless, one prokaryotic lineage is usually identified within the group, Cyanophyta (blue-green algae); and nine eukaryotes: Prochlorophyta, Glaucophyta, Rhodophyta (red algae), Cryptophyta, Chlorophyta (green algae), Euglenophyta, Chlorarachniophyta, Pyrrophyta (dinoflagellates), and Chromophyta (heterokonts) [22,23].

They are widely distributed in a variety of environments such as freshwater, seawater, surface waters, water columns, deep waters, and sediments, as well as terrestrial environments, including soils rich in organic matter and sand, both in warm and cold regions, and even in extreme regions such as Antarctica [11,14,21,24]. In Colombia, through metagenomics and microbial ecology approaches, microalgae have been identified in rivers, swamps, and hot springs in different regions of the country. Nevertheless, studies on microalgae diversity are scarce [13,25–28].

3. Nutritional Composition

The biochemical composition of microalgae makes their production attractive for the development of different biotechnological applications (Figure 1) [29,30]. Differences in the biochemical composition are observed depending on the species and a wide range of cultivation factors [31]. In this regard, many studies have focused on the chemical analysis of microalgal biomass and its response to different nutrient sources, light, and nutrient concentrations.

3.1. Proteins

Proteins are essential biomolecules for living beings, mainly because of their role as a source of nitrogen and sulfur. Protein content differs among organisms, accounting the highest percentage of dry matter in some microalgal species such as Arthrospira sp. (70%), Chlorella sp. (50–60%), Synechococcus sp. (65%), Dunaliella salina (57%), and Aphanizomenon flos-aquae (62%) [32,33]. Species such as Chlorella vulgaris, Arthrospira maxima, D. bardawil, Arthrospira platensis, and Nannochloropsis sp. contain high levels of essential amino acids such as leucine, isoleucine, valine, lysine, tryptophan, methionine, threonine, and histidine [33]. In addition, they produce non-essential amino acids, such as glycine, alanine, and tyrosine, which were found in higher levels in Scenedesmus sp. and A. platensis than in
conventional protein sources [33]. Therefore, microalgae are an alternative protein source with additional nutritional benefits to conventional animal and plant protein sources [34].

Figure 1. Biomolecules available in microalgae that are useful for human, plant, and animal nutrition.

3.2. Carbohydrates

Microalgae and cyanobacteria are important sources of carbohydrates. They produce large amounts of a wide range of polysaccharides for energy storage, as structural components (envelope, capsid, and slime), or are secreted (exopolysaccharides) [35,36]. Exopolysaccharides are used in industry as hydrocolloids, gelling agents, stabilizers, emulsifiers, and thickening agents [37]. Biologically, exopolysaccharides are synthesized in response to stress factors [38,39], and their composition differs among species or groups of microalgae (Charophyta, Rhodophyta, Ochrophyta, and Haptophyta) [40]. In general, they are heteropolymers. In cyanobacteria, the main monosaccharide identified is glucose [36]. Likewise, a high proportion of galactose, rhamnose, fucose, arabinose, xylose, and mannose can also be found in microalgae [35,41].

3.3. Lipids and Fatty Acids

Microalgae accumulate lipids for growth, cell division, and as energy reservoirs under stress conditions [42]. Over the past decade, the production of microalgae oils has focused on third-generation biofuels [43]; however, a wide range of potential applications can arise from their diverse lipid composition—saturated, monounsaturated, polyunsaturated, branched fatty acids, and fatty acid amides [44]. Under optimal conditions, the total lipid production by microalgae can exceed 50% of their dry biomass. Specifically, microalgae lipid profiles are rich in polyunsaturated fatty acids, such as omega-3, omega-6, docosahexaenoic acid (DHA), and eicosapentaenoic acid (EPA) [45]. Microalgae are primary producers of EPA and DHA in aquatic systems, which enables their sub-
sequent bioaccumulation in higher organisms. EPA and DHA may account for a high proportion of total lipids in microalgae, as observed in *Nannochloropsis* sp. (26–28%), *Phaeodactylum tricornutum* (39%), *Chlorella* sp. (39%), *Pavlova* sp. (36–41%), *Schizochytrium limacinum* (30–40%), *Thraustochytrium* sp. (45%), and *Isochrysis* sp. (28%) [15,45,46]. Microalgae also produce other essential fatty acids, such as alpha-linolenic acid, gamma-linolenic acid, linoleic acid, and arachidonic acid [47].

3.4. Vitamins, Pigments, and Antioxidants

Microalgae also produce other compounds of high commercial value, such as pigments, vitamins, and antioxidants. Chlorophyll, carotenoids, and phycobilins are the most abundant pigments in microalgae and cyanobacteria [15,48]. In addition to providing coloration, they possess health-promoting properties with potential in the pharmaceutical industry as antioxidants, vitamin precursors, neuroprotectors, and immunological stimulants [49]. The most used pigments, including beta-carotene, lutein, chlorophyll a and b, astaxanthin, and phycocyanin, are produced by *Botryococcus braunii*, *Chlorococccum* sp., *Scenedesmus* sp., *Arthrospira platensis*, and *Haematococcus pluvialis* [15].

Some microalgae are excellent sources of micronutrients, such as vitamin B12 (*Cylindrospermum* sp., *Tolypothrix tenuis*, *Nostoc muscorum*, and *Hapalosiphon fontinalis*), vitamin C (*Prototheca moriformis*, *Chlorella* sp., *Arthrospira* sp., and *Dunaliella* sp.) [15,29], vitamin E (*Euglena gracilis* and *D. tertiolecta*) [15,33], and other B-complex vitamins (B1, B3, B5, B6 in *Tetraselmis suecica*) [33].

Phenolic antioxidants such as rutin, hesperidin, morin, caffeic acid, catechol, and catechin are produced by some microalgae (*Nostoc* sp., *Chlorella* sp., *Anabaena* sp., *Tolypothrix* sp., and *Chlamydomonas* sp.) as secondary metabolites. Phenolic compounds act as free radical scavengers, hydrogen atom donors, and metal chelators. In view of these essential functions, they are used in food supplements [49,50].

4. Animal Feed

Some microalgal species have been used in animal feed, aquaculture, and beekeeping owing to their bioactive compound content [51–53]. The source of microalgal biomass can be either cultures destined to produce nutritional supplements or residual biomass from pollutant-free industrial processes, such as biofuel production [52,54–56].

In pig farming, the use of biomass supplements or microalgae oils has been shown to strengthen the immune system and improve animal health, thus enhancing the sensory characteristics and lipid composition of the meat [15,51,57,58]. Nutrition in pregnant sows and fattening pigs could be optimized using species such as *C. vulgaris*, *Arthrospira* sp., *Aurantiocystis limacinum*, and *Desmodesmus* sp.; in addition, production increases and the composition of fatty acids in meat improves, thus increasing the DHA content [57,59,60].

In ruminants, food supplementation with meal or oil from some species of microalgae has been explored [51,61,62]. As a result, improved organoleptic properties and fatty acid composition of meat and milk were observed in bovines [63–65]. Microalgae, such as *A. platensis*, were shown to be a good replacement for plant supplements, and improving the quality of milk [66]. Nevertheless, different species and concentrations need to be studied in bovines to avoid possible alterations in the organoleptic characteristics of meat [56,67]. In sheep, supplementation with *A. platensis* increased growth and development of animals, and *Schizochytrium* sp. improved meat quality [68,69]. Extracts from *C. sorokiniana* and *D. tertiolecta* exerted positive effects on anti-inflammatory activity and immunomodulation, enabling reduction in the use of antibiotics in pregnant or postpartum females [70,71]. Finally, supplementation with *C. vulgaris* in the diet of goats reduces oxidative stress, improving the quality of the milk since it has greater stability and better organoleptic characteristics [72].

In chickens and hens, food supplementation with microalgae has also shown beneficial effects on animal health and meat and egg production [15,51]. For instance, improved growth and meat quality, as well as a decrease in chronic diseases in broiler
chickens, were observed after supplementation with *C. vulgaris, A. platensis, Staurosira* sp., *Schizochytrium* sp., *Aurantiocytrium* sp. and *Amphora coffeaeformis* [51,73–76]. In laying hens, supplementation with *A. platensis, Nannochloropsis gaditana,* and *Porphyridium* sp. improved animal nutrition and health, as well as reduced cholesterol levels and enhanced organoleptic properties of the eggs [73,77,78].

Positive effects have also been observed in rabbits. *C. vulgaris* and *N. oceanica* improved the health, growth, and meat quality of animals [79,80]. The enormous potential of microalgae has also been studied in bees. The productivity, physiology, and health of honeybees improved when fed with microalgae [53].

In 2018, fish farming production accounted for 271,610 million USD and is estimated to generate 376,480 million USD by 2025. Therefore, the production of fish, crustaceans, mollusks, and algae is one of the most promising industries, with algae being extremely valuable [81]. Microalgae are essential in the feeding of aquatic animals [52]. The implementation of microalgae in fish farming is an environmentally friendly alternative to the non-sustainable fishmeal and fish oil-based feeds currently used. Microalgae have been successfully tested in salmon, trout, tilapia, ornamental fish, and crustaceans [51,82]. In farmed shrimp, feeding with *T. chuii, Dunaliella* sp., *A. platensis, Hypnea cervicornis,* and *Cryptonemia crenulata* improved both immunity and production [52,83]. Salmon and carp fed with *Nanofrustulum* sp., *Tetraselmis* sp., and *Haematococcus pluvialis,* and tilapia fed with *N. oculata,* and *Schizochytrium* sp. showed improved health and higher nutritional value compared to the meat [82,84–86].

The development of animal feed products based on microalgae is a promising field. However, a thorough knowledge of the characteristics of the species used, especially their cultivation, physiology, and secondary metabolites, is key to ensuring beneficial effects, high productivity, and efficiency. This is essential considering that some species of cyanobacteria and dinoflagellates produce molecules that are toxic to invertebrates and vertebrates [20,87,88].

5. Applications in Human Nutrition

The need for mass food production and the search for sustainable processes have led to the development of new strategies for food production with low impact on the environment. The use of microalgae as a food source has been studied since the late 1980s [89]; however, only in recent years has it generated greater interest. *A. platensis* (spirulina) is one of the most widely used microalgae. The interest in this microalgae for human consumption is based on the nutritional characteristics of its biomass, which are comparable to those of meat and soybeans, as well as on its vitamin, phenolic compound, mineral, amino acid, and essential fatty acid content [90].

In addition to basic nutritional properties, other benefits of microalgae for human health have been described [51,91,92]. For instance, foods supplemented with *Arthrospira* sp., *C. vulgaris, A. platensis, H. pluvialis,* and *D. salina* had positive effects on the anti-inflammatory activity, immune system, and properties that can regulate hyperglycemia and hyperlipidemia and protect against oxidative stress [15,51,91–96].

The biosafety and toxicity of lipid compounds extracted from *N. oculata, Rhodococcus opacus, Schizochytrium* sp., and *Cryptecodinium cohnii* have been assessed. These compounds are used as an alternative food to human breast milk. No cytotoxic effects were observed, supporting the feasibility of using microalgae oils for human nutrition from birth to 2 years of age or more [97–99]. Similarly, the composition and use of species such as *B. braunii, C. vulgaris, H. pluvialis,* and *Isochrysis galbana* have been studied. These species are an ideal vegetarian supplement because they contain essential amino acids, as well as omega-3 and omega-6 fatty acids [15,100].

Based on their high nutritional value, reduced environmental impact, and economic sustainability, microalgae have been used as functional ingredients to enhance the characteristics of foods [101], such as milk or dairy products [99] and meat products [90], or in the manufacturing of snacks [102,103], food supplements [104,105], and food pig-
ments [103,106]. This highlights the importance of research, development, and innovation in the use of microalgae for human consumption.

6. Agriculture

Crops can be greatly affected by the lack of phosphate. Novel alternative sources have needed to be developed due to the limited availability of this mineral and the negative impact that the application of inorganic phosphate compounds has on soils [107,108]. Phosphate is ubiquitously found in biomolecules and physiological processes in living organisms [109,110]. A viable option is the use of biomass for phosphate recycling [107]. In particular, microalgal biomass can provide an additional benefit because the biomass obtained from wastewater treatment can be used as an environmentally friendly fertilizer [16]. Microalgae are a feasible sustainable alternative and their use as fertilizers offers an opportunity to reduce the current dependence on agrochemicals that in most cases has secondary or detrimental effects [111]. Microalgae benefit plants by increasing nutrient availability, producing phytohormones, forming associations with roots, and protecting against pathogens and pests [16].

Some researchers have proposed that the mechanisms through which microalgae promote plant growth are associated with signaling and nutrition, such as the uptake of substances excreted by microalgae. However, these mechanisms remain unclear and further studies should be conducted in this regard [111,112]. Microalgae have been shown to be a feasible alternative to the use of chemical fertilizers because of their ability to accumulate nutrients in the form of polyphosphate granules [111]. The effects of microalgae on plant growth have been studied using species such as Chlorella sp., Gloecapsa sp., Oscillatoria amphibia, Microcystis aeruginosa, Synechococcus rubescens, and Cyanobium gracile [111,113,114]. C. vulgaris and C. sorokiniana promoted the growth of Triticum aestivum, releasing phosphate gradually and progressively over time [107,111,112]. Likewise, fertilization with Microcystis aeruginosa MKR0105, Anabaena sp. PCC7120, and Chlorella sp. enhanced plant growth and physiological performance by increasing cell membrane stability, chlorophyll synthesis, photosynthetic rate, stomatal conductance, and decreasing intracellular CO$_2$ concentration [115]. Finally, the biomass of Scenedesmus sp. was proven to be effective as a biofertilizer and can be applied in combination with chemical fertilizers, which may help to reduce excessive use of the latter [116].

7. Microalgae Production in Colombia

Microalgae are investigated and cultivated worldwide to search for new species and obtain a wide range of products. Countries such as the United States, China, Japan, and India are the main producers and developers of biotechnological advances [117,118]. In Colombia, there are few studies focused on the use of microalgae in food, animal production, and agriculture, despite the enormous potential of its biodiversity, water resources, climate, as well as the fulfilling needs driven by the high rates of poverty and malnutrition in the country [7]. In contrast, research in Colombia is mainly focused on the use of microalgae in the production of total lipids for biodiesel, wastewater treatment, and bioremediation [119–124]. Some research has recently begun in the agro-alimentary sector; however, little has been implemented in recent years (Table 1). In addition, there is increasing consumption of supplements based on microalgae, such as Arthrospira spp. and Chlorella sp., however, these are imported products. Therefore, these initial studies constitute a baseline for a promising future of the Colombian bioeconomy based on microalgae.
Table 1. Studies conducted in Colombia over the past 5 years on microalgae as a food supplement.

| Application | Microalga | Product | Conclusion | Reference |
|-------------|-----------|---------|------------|-----------|
| Human food  | Crypthecodinium cohnii | Yogurt with microalgae oil | Addition of microalgae oil increases DHA in the diet. | [124] |
|             | Arthrospira maxima | Biomass | Mass production of dry biomass (1 g/L) was accomplished by outdoor scale-up. | [125] |
|             | Scenedesmus sp. | Rotifer food | Increased population density was observed after feeding with Scenedesmus sp. | [126] |
| Animal feed | Chlorella sp. | Zooplankton food (Macrothrix spinosa) | M. spinosa fed with Chlorella sp. showed better performance. | [127] |
|             | Cylindrotheca closterium, Entomoneis alata, Plagiopitris lepidoptera, Komvophoron crassum, Synechococcus sp., Tetraselmis chuii | Food in marine aquaculture | Benthic microalgae showed potential for use as feed in marine aquaculture. | [113] |
| Agriculture | Gloeocapsa sp., Oscillatoria amphibia | Biofertilizer for rice, corn, and bean crops | Gloeocapsa sp. increased growth in rice plants by 15.0%. | [112] |
|             | Consortium of Microcystis aeruginosa, Synechococcus rubescens, Cyanobium gracile | Biofertilizer for gulupa crop | The results were similar to those of a traditional organic treatment. | [128] |
|             | Chlorella vulgaris | Lipid and carbohydrate production | Increased carbohydrates and lipids levels after addition of acetate, carbonate, and phosphate. | [129] |
|             | Botryococcus braunii | Fatty acids and exopolysaccharides | Galactose was the main component of exopolysaccharides (71.73%). | [130] |
|             | Chlorella sp., Scenedesmus sp. | Polyunsaturated fatty acids | Oleic acid was the major fatty acid present (28.75%). | [131] |
| Other uses  | Scenedesmus sp. | Carotenoids | C:N ratio affected biomass and carotenoid production. | [132] |
|             | Haematococcus pluvialis | Astaxanthin | The highest astaxanthin production was obtained in RM growth medium (8.3 µg/mL). | [133] |
|             | H. pluvialis | Astaxanthin | Higher concentrations of astaxanthin were obtained when limiting nitrogen and phosphorus. | [134] |

8. Conclusions

The global food demand, along with the need to develop environmentally friendly biotechnologies, urge the implementation of sustainable production models that consider social, environmental, and economic factors, which allow for fighting hunger and poverty, within the context of climate change, is both present and future challenge for Latin America and the world. In this regard, research and production projects conducted in several countries have shown that the use of microalgae in human food and animal feed, as well as in plant fertilization, offers multiple nutritional, economic, and environmental benefits. This industry has developed little in Colombia, but the climate and water resources available are advantageous for microalgae cultivation and production for the food industry, sustainable agricultural and livestock production, among other uses. In addition, the country’s native biodiversity provides opportunities for exploring new species with biotechnological applications in the food, pharmaceutical, energy, and environmental sectors. Therefore, the bioprospecting, cultivation, and use of microalgae could be an excellent strategy for the development of the bioeconomy in Colombia. Further studies and investments are required to better identify the country’s microalgae biodiversity and develop new sustainable biotechnological products. To do this, it is necessary to increase academic, investigative, technological, and productive capacities, implement public policies that promote these activities, as well as increase financing from the public and private sectors that allow for
the development of this considerable biotechnological and economic potential, which will contribute to the Sustainable Development Goals.

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