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Advancement of Algae as a Sustainable and Functional Food Source

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ABSTRACT

Current agricultural and food production practices are facing extreme stress, posed by climate change and an ever-increasing human population. The pressure to feed nearly 8 billion people while maintaining a minimal impact on the environment has prompted a movement toward new, more sustainable food sources. For thousands of years, both the macro (seaweed and kelp) and micro (unicellular) forms of algae have been cultivated as a food source. Algae have evolved to be highly efficient at resource utilization and have proven to be a viable source of nutritious biomass that could address many of the current food production issues. Particularly for microalgae, studies of their large-scale growth and cultivation come from the biofuel industry; however, this knowledge can be reasonably translated into the production of algae-based food products. The ability of algae to sequester CO2 lends to its sustainability by helping to reduce the carbon footprint of its production. Additionally, algae can be produced on non-arable land using non-potable water (including brackish or seawater), which allows them to complement rather than compete with traditional agriculture. Algae inherently have the desired qualities of a sustainable food source because they produce highly digestible proteins, lipids, and carbohydrates, and are rich in essential fatty acids, vitamins, and minerals. Although algae have yet to be fully domesticated as food sources, a variety of cultivation and breeding tools exist that can be built upon to allow for the increased productivity and enhanced nutritional and organoleptic qualities that will be required to bring algae to mainstream utilization.

INTRODUCTION

Algae are a large and diverse group of autotrophic eukaryotic and photosynthetic aquatic organisms [1]. They can be divided into multi-cellular seaweeds, and unicellular microalgae (including cyanobacteria) [2]. In the last years, there has been a growing interest in algae as an essential part of the food of the future. Using the Scopus database (Elsevier's abstract and citation database), a search was performed from 1990 to 2022, selecting "algae and foods" as keywords; a total of 17216 publications were obtained.

In the frame of the transition to plant-based diets, the use of algae as food ingredients has received considerable attention as a sustainable food source for human nutrition [1]. Compared to conventional plant- and animal-based sources, algae are highly productive and do not require arable/fertile land and do not need fresh water sources. Algae also may contribute into sixteen sustainable development goals of the 2030 agenda [3]. However, algal ingredients are mostly used as dry powder or derived products and not as a wet biomass. Considering that drying is a cost-intensive and energy-requiring process, innovative technologies such as indirect hybrid solar dryer was tested for drying microalgae (*Tetraselmis chui* and *Nannochloropsis oceanica*) wet paste [4]. Results revealed that the nutritional (total proteins, carbohydrates, lipids, and fatty acid profiles) and functional properties (solubility, water-, oil-holding, foaming and emulsifying properties) as well as the microbial safety of solar dried microalgae were comparable to those obtained from conventional methods (freeze or spray drying). Furthermore, the upscaling of solar dryer could contribute into reducing the cost of production and consequently boosting the market of algae ingredients beyond niche to mainstream.

As functional ingredients, algae offer a vast range of health-beneficial compounds such as protein, bioactive peptides, fatty acids, polysaccharides, sterols, minerals, and vitamins [5,6,7,8]. In a recent study, Afonso et al. [6] showed that the nutritional benefits of algae species can be further maximized through the modulation of the environmental conditions. Scientific evidence demonstrated several health promoting properties such as antioxidant, scavenging, reducing, and anti-proliferative activities in relatedness to algal phenolic and flavonoid contents [5]. Furthermore, based on in vivo trials, the combination of sulfated polysaccharide ulvan and the carotenoid astaxanthin promoted the relative abundance of *Bacteroidia*, *Bacilli*, *Clostridia*, and *Verrucomicrobia*, which are beneficial for intestinal health and gut homeostasis [9].

Thus, the use of algal ingredients is trending upward in commercial foods as reported by a recent market study [10]. It was found that the dominant algal ingredient is carrageenan owing to its thickening, emulsifying, stabilizing, and gelling features, while the main species used are *Chlorella* spp. and *Arthrospira* sp., '*Spirulina*' [10]. Recent research evidence revealed that microalgae can be successfully incorporated in vegetables creams [11], snacks [12] and pasta [13,14]. Boukid et al. [11] developed high-protein vegetable creams using single-cell ingredients from *Spirulina*, *Chlorella vulgaris*, *Tetraselmis chui*, and *Nannochloropsis oceanica*. This addition (1.5 and 3%) improved the nutritional quality but impacted the physicochemical and rheological properties of the creams at different extent depending on the species and the level of addition. Creams made with 1.5% *C. vulgaris* were found comparable to the standard product (without microalgae). Bazarnova et al. [13] incorporated 5% of *Chlorella sorokiniana* in durum wheat pasta, which improved the nutritional quality (proteins, lipids, chlorophyll, and carotenoids) and provided a natural red color to the final product [13]. Compared to 100% durum wheat pasta, the incorporation of seaweeds (3% of *Ulva lactuca*, *Porphyra tenera*, and *Undaria pinnatifida*) improved the nutritional value and induced slight changes in the technological properties of enriched pasta [14]. To avoid nutrients

deterioration during high temperature treatments, Tork et al. [12] used *Spirulina* as a dragée for the coating of extruded corn snack. This dragée provided snacks with improved nutritional quality (flavonoids, anthocyanin, vitamins, protein, minerals, and fatty acids, including ω3 and ω6) and high sensory scores.

Thus, even though the food market has strong motivations to include algae ingredients [2], the maximum inclusion level did not exceed 5% in most cases due to their peculiar color and umami taste (depending on the species) [11,12,13,14]. More research is deemed necessary for selecting new strains as well as developing technologies (e.g., purification and encapsulation) to enhance the organoleptic profile of algae and thus favor consumers acceptance. Furthermore, several bottlenecks including high production costs, health concerns related the toxicology and allergenicity of some species, and unclear legislation need to be addressed to boost unlocking the potential of algae [2].

DISCUSSION

Global population growth, projected to reach 9.3 billion by 2050, poses significant challenges to food production and the traditional food supply system. In this context, microalgae offer a sustainable solution for global food security. With their carbon sequestration capacity, nutrient richness, and photosynthetic efficiency, microalgae have the potential to become essential in achieving carbon neutrality and meeting future food demands. However, several challenges must be addressed, including high production costs, low acceptance, and safety concerns. Coordinated efforts from various fields are required to overcome these challenges and unlock the full potential of microalgae-based food development. This review article discusses the benefits, drawbacks, and future prospects of microalgae as food and feed sources. It covers topics such as their nutritional compositions, economic feasibility, sustainability, and market trends. Additionally, the article discusses essential aspects, including safety, environmental impact, cost, functionality, and ongoing research efforts. Overall, this comprehensive review aims to shed light on the potential of microalgae as a viable solution to address global food security challenges while also addressing the hurdles that must be overcome for their successful implementation in the food industry.[10,11]

Offering a potential solution for global food security and mitigating environmental issues caused by the expansion of land-based food production, the carbon-hunger and nutrient-rich microalgae emerged as a sustainable food source for both humans and animals. Other than as an alternative source for protein, microalgae offer its most valuable nutrients, omega-3 and 6 long-chain polyunsaturated fatty acids where the content can compete with that of marine fish with lower chemicals contamination and higher purity. Furthermore, the colorful pigments of microalgae can act as antioxidants together with many other health-improving properties as well as a natural colorant. In addition, the supplementation of algae as animal feed provides plentiful benefits, such as improved growth and body weight, reduced feed intake, enhanced immune response and durability towards illness, antibacterial and antiviral action as well as enrichment of livestock products with bioactive compounds. The significant breakthrough in algal biotechnology has made algae a powerful "cell factory" for food production and lead to the rapid growth of the algal bioeconomy in the food and feed industry.

Subsequently, the nutritional compositions of microalgae were discussed together with its applications in human foods and animal feeds, followed by the exploration of their economic feasibility and sustainability as well as market trends. Lastly, both challenges and future perspectives were also discussed.

RESULTS

Microalgae have recently attracted considerable interest worldwide, due to their extensive application potential in the renewable energy, biopharmaceutical, and nutraceutical industries. Microalgae are renewable, sustainable, and economical sources of biofuels, bioactive medicinal products, and food ingredients. Several microalgae species have been investigated for their potential as value-added products with remarkable pharmacological and biological qualities. As biofuels, they are a perfect substitute to liquid fossil fuels with respect to cost, renewability, [12,13]and environmental concerns. Microalgae have a significant ability to convert atmospheric CO_2 to useful products such as carbohydrates, lipids, and other bioactive metabolites. Although microalgae are feasible sources for bioenergy and biopharmaceuticals in general, some limitations and challenges remain, which must be overcome to upgrade the technology from pilot-phase to industrial level. The most challenging and crucial issues are enhancing microalgae growth rate and product synthesis, dewatering algae culture for biomass production, pretreating biomass, and optimizing the fermentation process in case of algal bioethanol production

Algae are known as cell factories that can convert sunlight, water and carbon dioxide into biomass. Algae, commonly classified by their size (microalgae and macroalgae), are heterogeneous groups of organisms that can vary greatly. Algae contain high amounts of lipid (20-80%), protein (39-71%) and dietary fiber depending on species, the region where it grows, the season, the way of harvesting, storage conditions and food processing techniques. Moreover, due to their there are sterol, vitamin, pigment, α-tocopherol, β-carotene, glutathione, ascorbic acid, flavonoids, hydroquinones, phycocyanins, proline, phenolic compounds, polyamines and polyunsaturated fatty acids (ω-3 fatty acids) contents, they are considered as good food sources and are used in the production of functional food. Thanks to these valuable bioactive components, algae are thought to have antioxidant, antimicrobial, anti inflammatory and anticarcinogenic effects. The country with the highest consumption of algae, which is a part of the human diet for many years, is Japan. China and Indonesia lead the way in algae production. In addition to its use as food, algae is preferred as a raw material in the production of food supplements, animal feed, in the cosmetics and pharmaceutical industries, and in the production of bioenergy and biofuels. Algae are also used in greenhouse gas emission reduction and biological remediation applications, as well as their usage as nitrogen-fixing biofertilizers. In this study; information about the composition, properties, classification, production and harvesting of algae as well as algal oil is given. The aim of the study is to draw attention to a resource that is sustainable, alternative, innovative and has a high potential for better evaluation and to provide information about the introduction of algae as a source of ω-3 and the inclusion of foods enriched with the use of algae in the human diet as supplements.[14]

Seaweeds are edible algae that have been used for centuries as food all over the world. Algae are of excellent nutritional value since they contain complete protein, fiber, and sometimes high levels of omega-3 fatty acids. In fact, the omega-3 acids in fish come from the microalgae consumed at the bottom of the food pyramid and gradually passed up to the fish at the top. Algae are also rich in many vitamins, such as A, C, B1, B2, B3 and B6, as well as minerals, such as iodine, calcium, potassium, magnesium and iron. They can be consumed from cooked to dried or raw (Siva Kiran et al., 2015) [34]. Algae are used for some production such as Medicines, vitamins, vaccines, nutraceuticals and other nutrients. Many types of algae and the products derived from them have shown medicinal values and nutritional applications. *Spirulina* is a form of blue green Algae that springs from warm, fresh water bodies. It is often confused with chorella, but the fundamental difference between them is that *Spirulina* does not possess the hard cell wall while chlorella possess a hard cell which makesit closer to being a plant than algae. *Spirulina* is renowned for its intense flavor and even more powerful nutrition profile. *Spirulina* benefits are so amazing that when taken on a daily basis they could restore and revitalize the health (Nicoletti M. 2016) [9,10]. *Spirulina* is being seriously discussed as a sustainable source of food with its potential to end world hunger it is different from most plants, because it is able to withstand extreme temperature variations and still thrive. It has been found in studies to successfully treat a wide range of ailment, including arsenic poisoning, candida overgrowth, and allergic rhinitis. It has also been seen to potentially lower stroke and cancer risks. *Spirulina* as a super food is a plant that can nourish the body by providing most of the protein require by the body. It helps to prevent the annoying sniffling and sneezing of allergies, reinforces the immune system, helps to control high blood pressure and cholesterol and helps to protect against cancer. The recommended daily dose is typically 3-5 grams, which can be spread out twice to thrice a day. It is a powerhouse of essential vitamins and minerals, it is also a potent. Mostly people take availability of healthy clean water for granted, unfortunately in some countries like Bangladesh, it is a luxury. Bangladesh water supply is loaded with arsenic. Bangladeshi researchers conducted a three-month-hospitalbased study, where *Spirulina* was given to 33 patients while 17 received placebo doses. 82 percent of those taking *Spirulina* showed tremendous improvement. According to one study, Cingi et al., 2008 [10], patients treated with *Spirulina* reported relief of symptoms commonly associated with allergic rhinitis, such as nasal discharge and congestion, sneezing and itching. *Spirulina* helps to regulate blood pressure among both women and men ages 18-65 years with no other dietary changes and lower cholesterol levels. *Spirulina* is healthy for vegetarian because it contains 65-71 percent complete protein compared to beef, which is only 22 percent, and lentils, which is only 26 percent. In addition to being protein-rich, *Spirulina* is an excellent source of vital amino acids and minerals easily assimilated by the body. There are many types of *Spirulina* out there so it is important to choose organic *Spirulina* from a reputable source. *Spirulina* comes in capsules, tablets, powders and flakes. *Spirulina* is a safe source of protein, nutrients, vitamins, and minerals that has been used for centuries, though there are no known side effects associated with *Spirulina*, the body may react to it based on individual current state of health. The reactions can be reduced by increasing the water intake, reducing stress levels, eating according to nutritional type and getting plenty of rest. Some major benefits of *Spirulina* include; • It helps in detoxification of Heavy Metals especially Arsenic. According to the World Health Organization 2016, the United States is one of the countries affected by inorganic arsenic that is naturally present at high levels. Millions of people in Bangladesh, India, Taiwan and Chile are consuming high concentration of arsenic through drinking water, and thousands of them have already developed chronic arsenic poisoning. After giving 24 patients affected by chronic arsenic poisoning *Spirulina* extract (250 mg) plus zinc (2 mg) twice daily, they compared the results with 17 patients who took a placebo and found that the *Spirulina*-zinc combination worked wonderfully. Ultimately, the participants experienced a 47% decrease of arsenic in their body. • It helps in eliminating Candida with its effective antimicrobial agent. Specifically, the immune-strengthening properties of *Spirulina* help to promote the growth of healthy bacterial flora in the intestines, which in turn inhibits Candida from thriving. • It helps to lower the Blood pressure; Phycocyanin is a pigment found in the *Spirulina* that scientists have discovered possesses antihypertensive effects (Ichimura M et al., 2013) [25]. Japanese researchers claim that this is because consuming the blue-green algae reverses endothelial dysfunction in metabolic syndrome because metabolic syndrome has rapidly become one of the main causes of preventable disease today, as it raises one's risk of developing heart disease, diabetes and stroke. • It helps to lower Cholesterol[11,12,13] and reduce chances of Stroke. *Spirulina* have shown to prevent atherosclerosis and reduce elevated blood cholesterol levels. • It helps to boost Energy When *Spirulina* and lime are combined it enhances energy performance because they unlock sugar from the cells and, when frozen, the cold from the ice boosts metabolic energy while it gives the body a "wake-up call." • It speeds up weight loss *Spirulina* promotes weight loss and low-fat stores through a variety of mechanism because it takes more energy to metabolize and they are high nutrient-dense protein-rich foods. • *Spirulina* benefits the body by reducing the inflammation that causes people to experience sinus problems known as allergic rhinitis and it is effective at reducing itching, nasal discharge, nasal congestion and sneezing. An average of one ounce of different *Spirulina* species contains the following nutritional content: Calories (81), Protein (39g), Dietary fiber (1g), Sugars (.9g), Fats: Total fat (3% Daily Value), saturated fat (4%), Omega-3 fatty acids (230 mg), Omega-6 fatty acids (351 mg). Precautions of high consumption of Algae Consumption of any food is not without risk, so the precaution of high algal consumption must also be considered t consumes to prevent potential harm. Possible risks associated with algae include excess intake of toxic metals, allergenicity, cyanotoxins, and certainly secondary metabolites (e.g., prostaglandins, kainoids) as well as contamination with pathogens, radioisotopes, and toxic synthetic compounds. Algae are being grown in waters enriched with carbon dioxide, climate-changing waste gases that can be pumped into algae ponds from mines, power plants, and factories. *Spirulina* is a strong detoxifier that why it is best to start with a small dose and allow the body adapt to it. Heterotrophic microalgae are grown in large fermenters using sugar or starch, similar to the corn ethanol fermentation already providing almost 10 percent of our liquid transportation fuels. Seaweeds (macroalgae) are cultivated in seawater, typically in near-shore systems, though open ocean cultivation has been

studied in the past and are again of interest, and even on-shore cultivation of seaweeds is a possibility. A number of algae production technologies are currently under development, from open ponds and closed photo bioreactors, from fermentation tanks to hybrid systems, to some that combine these various methods. Simply put, there is no one single way to grow algae at commercial scale, and this versatility is one of algae's strengths. The most prominent reactions from *Spirulina* can be; Slight Fever due to high protein content, Dark Green Waste Matter due to high chlorophyll, Hyper-activeness due to conversion process of protein into heat energy and Sleepiness from the detoxification process and may indicate your body is exhausted and needs better rest.[14]

CONCLUSION

This review emphasizes the relevance of algae as a functional food, which is not known by some countries due to ignorance despite the abundance of the edible algal species. Even though *Spirulina* is entirely natural and generally considered a healthy food, there are some contraindications to be aware of such as allergy to seafood or iodine and pregnant or nursing women. *Spirulina* is generally considered safe for human consumption supported by its long history of use as food source. Quality control in the growth and process of *Spirulina* to avoid contamination is mandatory to guarantee the safety of the products. The use of algae should be encouraged because it will help solve so many environmental problems like purification of water and enhance usage of barren land. [14]

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