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Algal Resources Exploitation for Green Economy and Sustainable Development: A Review

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Abstract

Global issues such as environmental degradation, hunger and malnutrition, poverty, antibiotic resistance, chronic diseases, depletion of fossil fuels and other issues associated with their utilization, among others, are burdening the global population's quality of life. Algal resources are well-positioned, prominent, and sustainable resources for providing some solutions to global challenges such as malnutrition, antibiotic resistance, and environmental degradation. Algal resources play a dual role, which is feedstocks with a broad range of applications (including healthy foods, food supplements, feeds, and bio-energy) coupled with environmental phycoremediation. This review article is amained to elucidate the potentials of algal resources from the current scientific literature and to highlight their inputs in solving current pressing global challenges. The approaches and strategies that can contribute to the achievement of sustainable development through the utilization of algal resources are also discussed.

Graphical Abstract

Keywords: Algal resources; Climate change; Food security; Healthy food; Sustainable development

Introduction

At the center of the green economy and sustainable development are human beings and their entitlement to a harmonious, healthy, and productive, life with nature [1]. Human health and quality of life are confronted with various harsh conditions, including climate change, burden illness, antibiotic resistance, and the side effects of medication, among others. Chronic diseases, malnutrition, and antibiotic resistance are the pressing global health challenges, which are the important cause of illness, disability, and death while there are some possibilities to prevent them [2]. There is also an imbalance between available natural resources and global population growth as more demands are placed on natural resources to meet human needs. This gap is further aggravated by climate change effects where nonrenewable resources are being depleted, and arable soils are becoming infertile, as well as other related challenges [3]. Apart from hampering human health, the quality of life is also negatively affected, especially global sustainability and development because the green economy and sustainable development cannot be discussed without food security and nutrition that have concomitant relation with longevity and quality of life.

In order to achieve harmony, the global community has set several goals in which healthy human populations, sustainable development, and the green economy are linked. In 2012, the international community reaffirmed its commitment to sustainable development and past action plans with the outcome document "The future we want" at the United Nations Conference on Sustainable Development (SD) in Rio de Janeiro [4] which was endorsed by the United Nations General Assembly shortly after [5]. The Food and Agriculture Organization of the United Nations (FAO) has the goal of achieving zero hunger, food security and improved nutrition by 2030 (SD-goal 2), and good health and well-being (SD-goal 3) that may contribute to the promotion of human health and quality of life [6]. Nevertheless, the World Health Organization (WHO) reported that prevention of chronic diseases is a vital investment as chronic diseases, especially cancer and diabetes, will keep increasing within the same range of time and new cancer cases will increase in number up to 22 million within the next 20 years worldwide [7,8]. Among the many avenues to achieve these global goals is through scientific research and application to satisfy daily needs and future development [9].

This article highlights some global challenges hindering the achievement of sustainable development and describes algal resources inputs in the resolution of these pressing global challenges and achieving sustainable development. Natural resources are continuing to be depleted while the global population continues to increase [10]. This imbalance is the reason why researchers are interested in the exploitation and management of renewable natural resources for future betterment.

Nutrient-rich foods (with all essential nutrients), also termed as rainbow food or complete food, help prevent and control various diseases due to their physiological activities. Taking daily complete food can improve the self-protection and self-healing capacity of the body, thus leading to a healthy body [11].

Referring to the available scientific literature, and some algal derived products available on the global markets with prominent health promotion; algal resources are one of the potential natural sources of food with essential nutrients [12], that can contribute to the achievement of the availability of nutrient-rich foods with health benefits, and zero hunger goal (Figure 1). Algal resources are considered one of the promising and sustainable resources to be exploited in various industrial fields [13], due to their enormous biochemical composition including essential nutrients, functional ingredients of food and pharmaceuticals [12]. Algal resources exhibit several advantages (see Supplementary Material S1) that makes them part of the plausible inputs to achieve sustainable development [14].

Because of the mentioned advantages and potential, algal resources have mesmerized the attention of many researchers for their amply exploitation and utilization in resolving some life challenges. The integration of algal-derived functional foods and nutraceuticals in food security and nutrition would be considered as one alternative intervention to promote human health and quality of life.

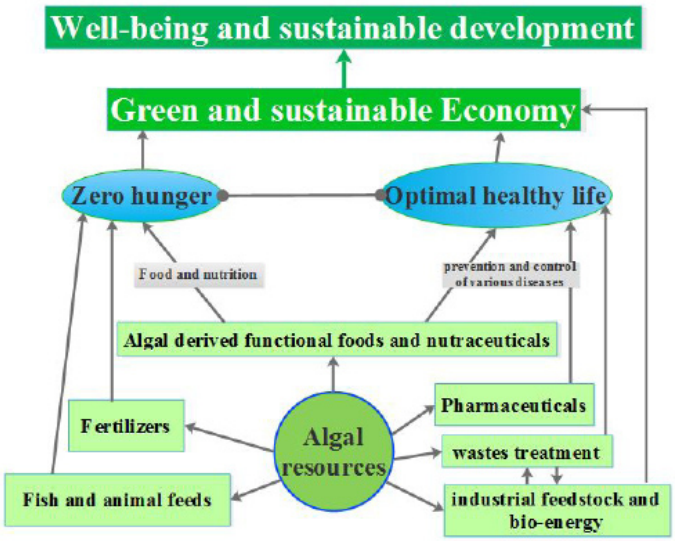

Figure 1: A conceptual schematic diagram of the input of algal resources in the achievement of Zero hunger and Good health and well-being goals as ones of the keys for sustainable development**.**

As far as the authors are aware of algal resources exploitation and sustainable development goals, no other articles are summarizing the integration of algal resources in the whole systems for human well-being and sustainable development. Therefore, this review article focusses not just on the efficacy of algal-derived functional foods and nutraceuticals for a healthy life but it also highlights other opportunities in the exploitation of algal resources that can contribute to the achievement of sustainable development and green economy.

Challenges Hindering Sustainable Development Achievement

Various global challenges hinder the achievement of sustainable development goals. Some of those challenges linked to climate change and malpractice of agriculture are food security and nutrition, chronic diseases, and antibiotic resistance. Climate change and conflict zones may be considered as leading causes of food insecurity, which subsequently lead to inadequate living conditions. Climate and environmental change are also behind infectious and non-communicable diseases and malnutrition [15]. The latter three main challenges are somehow interconnected and interdependent. For example, antibiotic resistance has one of the roots associated with food production because of the overuse of antibiotics in livestock as a growth promoter and disease preventer [16]; and water resources contamination with waste-derived fertilizer residues because of its overuse [17] (Figure 2).

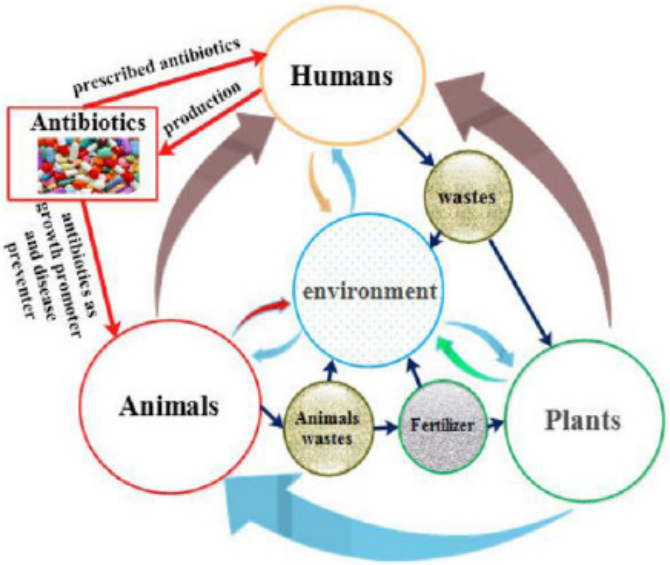

Figure 2: Channels toward human antibiotic resistance.

Also, the imbalance between global population growth and available resources cannot be ignored. Unsafe lifestyle and diet related-diseases including diabetes are also a problem among current global health challenges that are causing disabilities and deaths (For detailed information, about the challenges and current strategies and policy, see supplementary material S1).

Current global population growth raises and imposes the need for an integrated and sustainable food policy [18]. That policy should provide technologies and knowledge about complete healthy food production, which aims to promote health and help prevent disease and a reduced risk of diet-induced diseases. The complete healthy food contains nutrients and other substances (such as phytonutrients, omega facts acids, pre- and probiotics) that not only nourish the body but also promote human health and protection from health-related problems, including chronic diseases (Figure 3). Therefore, there is a critical requirement for the promotion of sustainable and supportive food sources for agricultural foods to tackle undernourishment and achieve food security and nutrition.

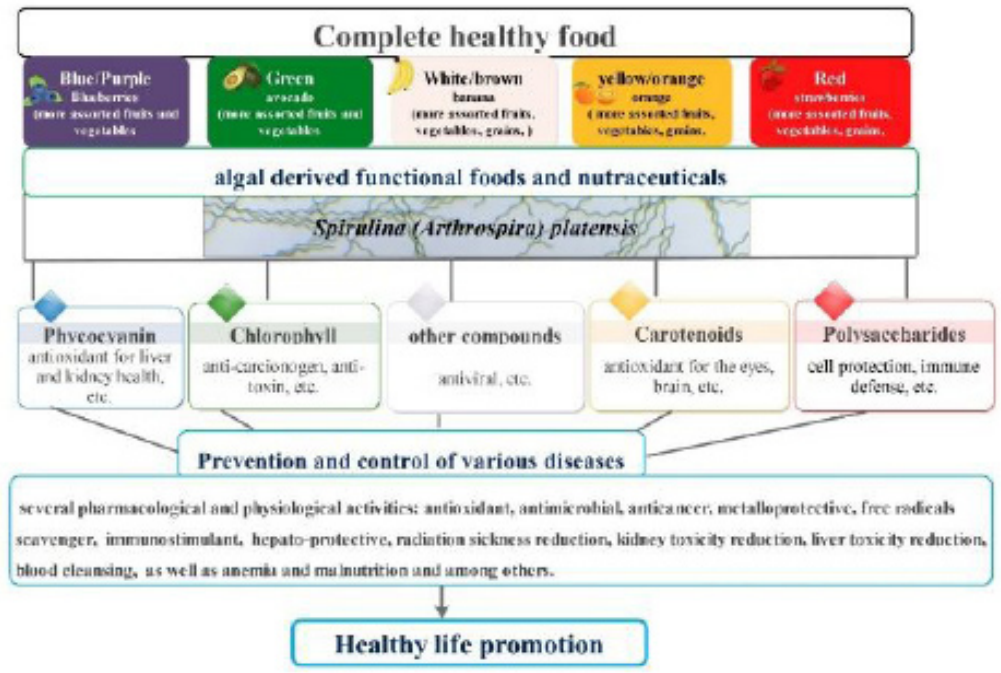

Figure 3: Algal derived functional foods and nutraceuticals, potential, suitable, and adequate superfood for preventing and controlling various diseases, especially chronic diseases.

Why are algal resources plausible inputs for achieving sustainable development and the green economy?

Natural resources are continuing to be depleted while the global population increases. This is the reason why the researchers are fully interested in the exploitation and management of renewable natural resources for future betterment. The algal resource can produce feedstocks with a broad range of compounds that can be applied in food, feed, pharmacy, cosmetics, biofuels, and biotechnology industries, to mention just a few [19, 20]. Based on the several advantages associated with algal resources including eco-friendliness, high efficiency (as detailed in S1); utilization of algal resources can contribute to a green economy and sustainable development through the promotion of human welfare and quality of life [21] (Figure1).

Algal resources (i.e., microalgae, macroalgae, and *cyanobacteria*) are many species [22] with different genetic, morphological and physiological characteristics that confer the ability to produce many bioactive compounds with several biological [23], and pharmacological activities [24,25] that can be exploited in various industries. The composition profiles of algal species have attracted many researchers from prestigious research centers and high-ranked universities for their exploration. The selection of algal species/strains and culturing modes depend on the compounds of interest and utilization of produced biomass [26] (Figure 4). For example, *Spirulina sp*., *Chlorella sp. Anabaena sp.*, *Nostoc sp.* are recognized for bioactive substances that are mainly applied in food, health food, nutraceutical, and pharmaceutical fields due to their functional food, physiological and pharmaceutical properties [27]. *Botryococcus braunii* is recommended for biofuel production due to its high lipid content (up to 78%) [28].

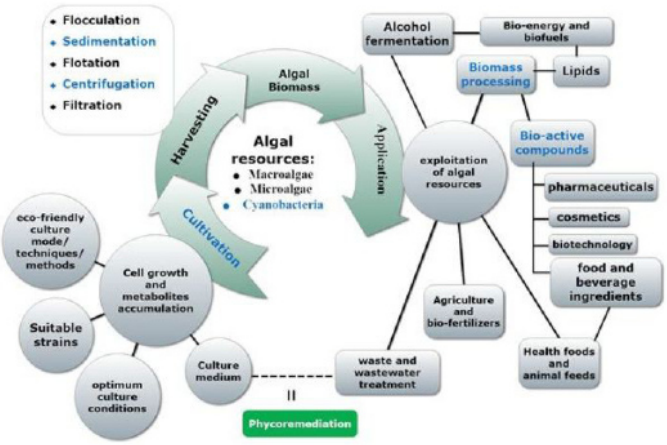

Figure 4: Flowsheet of algal resources production process and applications

Algal derived products also play an important role in the world economy [14], wherein 2001 the turnover was approximated to US$ 5 billion per year [29], and continues to increase: currently,

the algal-based nutraceuticals market is estimated to have reached US$ 2.5 billion by 2018. According to Global Algae Products Market 2017-2022 report, the market is expected to increase up to US$ 3.3 Billion by 2022 [30].

Algal derived foods, health foods, nutraceuticals and their input in human health and food security and nutrition

Algal derived foods are one of the most nutrient-rich food sources for new sustainable food and functional food products due to their high growth rate, high productivity, and macro- and micro-nutrients with many health benefits [31,32]. They can be used to enrich the nutritional value of foods and in return, promote health due to their well-balanced chemical composition, especially bioactive compounds with prominent benefits for animal and human health [33]. For instance, the nutritional values of algal resources are higher compared to a fish meal because they contain digestible complete proteins, lipids, and carbohydrates, as well as micronutrients [34]. The algal derived foods, especially Spirulina, have been traditionally considered and utilized as a potent source of proteins for many years in some countries, including Japan, Chile, and North America [35]. Recently, scientific studies show that algal resources are an adequate and sustainable source of bioactive molecules, especially for enhancing the nutritional and functional quality of foods [36].

The algal species that are commonly used in food, health foods, food supplements, and nutraceutical fields are *Spirulina platensis, Chlorella vulgaris, Daniella salina, Aphanizomenon flos-aquae, Schizochytrium,* and *Haematococcus pluvialis* [37] but *Spirulina* and *Chlorella* are most prominent due to available extensive research, and wide range of compounds, especially proteins, that are applied in the food and medicine industries as healthier food products [35,37]. Spirulina is the most well-known and applied due to its macro- and micro-nutrients with health benefits (Figure 5) including complete and digestible proteins with all essential amino acids and non-essential amino acids, fatty acids, vitamins and minerals [36,38]. *Chlorella* is also a potent asset in human health and nutrition due to nutritional contents where it can lower oxidative stress, boosts the immune system, and health-promoting factor by controlling other kinds of disorders such as wounds, constipation, and anemia, among others [39].

Figure 5: Main nutritional composition of a typical product of Spirulina from Yunnan Green A Biological Project Co., Ltd. located in Kunming, Yunnan, China. a. a copy from the company, b. scanned from package box with permission from the company.

The food industry has to keep exploiting the potential of algal-derived products as prominent sources of health-promoting products [36,40]. Based on tangible results from scientific research studies, global demand for algal-derived foods is growing, and their demands have been increased due to their functional benefits [35]. The algal derived functional foods, and nutraceuticals can be an adequate and sustainable supportive food source with components of the human diet that can reduce the risk of diseases and promote human well-being as well as livestock welfare. Therefore, the algae-derived products can be used for fortification of conventional foods with the cost-effective process [41,42].

The algal derived foods' health benefits are also associated with their nature and characteristics. 1) Algal derived foods are alkaline foods, which are needed by the human body at a rate of 80 % and some of them exhibit high digestibility (83-90%) [32]. 2) Algal resources are not only producing essential nutrients (i.e., proteins, fats, polycarbohydrates, minerals, vitamins) but also produce many other bioactive compounds such as Superoxide Dismutase (SOD), phycobiliproteins, carotenoids, flavonoids, glucosides, terpenoids, Polyunsaturated Fatty Acids (PUFAs) (including Docosahexaenoic Acid (DHA), Linolenic Acid (GLA) and Eicosapentaenoic Acid (EPA)) and phenazines among others [32,37]. These bioactive compounds are irreplaceable ingredients in the food industry, as well as other fields, due to various physiological, therapeutic and pharmacological activities that can prevent and control various diseases related to diet-induced, cell damage diseases and improving the quality of life.

Most diseases are linked to cell damage and malfunction such as cell deficiency in nutrient energy, cell inflammation, cell dysfunction and cell toxicity [43]. Those cell problems, in turn, can lead to pre-mature cell-aging. The algal derived compounds are among promising bioactive compounds that can prevent cell damage and malfunction where those compounds can act as an antioxidant, anti-inflammatory, and antimicrobial, as well as release the side effects of free radicals in the human body [14,24,44]. Niu, Zhou, Guo, Nie, Shin, Kim, Lv and Cui [45] reported that phycocyanin could protect against mitochondrial dysfunction and oxidative stress in parthenogenetic porcine embryos. Lycopene, also known as phytonutrient, is a phytochemical with antioxidant activity that belongs to the group of carotenoid pigments. It helps protect cells by neutralizing free radicals, and it can positively affect the immune system, as well as other health benefits [46]. The consumption of a diet rich in antioxidant lycopene may help prevent and control various kinds of cancers such as prostate, breast, stomach, throat, and lung cancers in the human body [47], as proven in animal models [48]. SOD is a potent antioxidant enzyme, which plays a role in eliminating toxins in the human body, [49]. Astaxanthin, lutein, Zeaxanthin are carotenoids that can act as free radical scavengers and can also intervene in boosting visual and healthy immune functions by reducing eye irritation, fatigue and improve the quality of vision [11,50,51]. Food with PUFAs ω-3 and ω-6 compounds possess well-documented improving human health, protecting, controlling and healing properties against various diseases including chronic diseases [31,52]. It is in this line that microalgae as a prominent source of long-chain polyunsaturated fatty acids including omega-3 and omega-6, and other nutritional compounds, are considered as prominent and sustainable foods for humans.

Probiotics are a heterogeneous group of non-pathogenic bacteria that help the body to absorb important nutrients (including vitamins and minerals) for body function, growth and maintenance, thus leading to a healthy body [53,54]. Algal resources are among promising prebiotics that helps promote the proliferation of probiotic in the gut thus leading to the promotion of human body immunity through different metabolic mechanisms. The dietary components including nutrients and phytochemicals are also regarded as dietary interventions in the perspective of cancer chemoprevention [55] where algal resources can play a vital role as sources of those nutrients and phytochemicals. Nutritious and health food promotes human health, and in return will reduce antibiotic prescription, which is one way of antibiotic resistance development (see Supplementary Material S1).

Different companies worldwide are currently considering the importance of algal-based resources and are trying to utilize them for high-value food products different from tablets, capsules, and powders, to minimize the negative connotation regarding algal derived foods, which in return can boost the exploitation of algal resources in the food industry. For example, a Dutch company launched dark chocolate containing 3 g of Spirulina [56]; Iranian Scientists produce sweets for people with diabetes using Stevia and Spirulina [57]. Furthermore, algal-derived products are used to fortify foods such as snacks for enhancing nutritional content [58,59]. This process of enrichment of foods should also consider sensorial characteristics including color, flavor, taste, and texture that could increase the customer's intention of acceptance and purchasing [59].

Algae for Pharmaceutical and Therapy

Antibiotic resistance and cancers are a growing health problem worldwide that urgently needs the formulation and production of new drugs, and the provision of other means of prevention and control. Those new drugs should be effective in treating new diseases causing infections. Generally, natural products are a prominent source of new structures leading to drug formulation and production for most diseases. It is promising that algal derived bioactive compounds can also contribute to the development of new therapeutic and drugs development because the therapeutic effects of natural product-derived drugs are preponderantly achieved in antibiotic therapies and immune regulation [25].

Based on the tremendous algal derived bioactive compounds with several pharmacological and biological functions [24,60,61] including antibacterial, antimicrobial, anti-inflammatory, antiviral, anticancer, immunomodulating, antihyperlipidemic, antioxidant, antiallergic, and antiprotozoal [62-65]. It is in this sense that algal resources are a sustainable source of ingredients to be exploited in the pharmaceutical industry [66]. The fact that algal resources are very prolific and synthesize biologically active compounds like drugs have exhibited auspicious and plausible results through animal and clinical tests for various dreadful human diseases [65]. Therefore, algal resources are natural resources that provide a promising opportunity for new drug discovery for therapeutic entities [25,61].

Furthermore, algal-derived products can also promote human health while they are taken in their raw states such as Spirulina and or *Chlorella* powders, tablets and capsules. For example, *Chlorella* (also known as a detoxifying agent), which is rich in Chlorophyll, lutein, beta-carotene and Vitamin E, is known to provide several health benefits such as strengthening the immune system, lowering the oxidative stress and enhancing anti-tumor immunity [52]. Researchers from innovative cancer therapy of Kureme University, Japan and *Chlorella* Industry Co., Ltd., conducted a study for the quality of life in Breast Cancer patients (forty-five female patients in three groups randomly assigned) by using *Chlorella* extract drink, *chlorella* granules, and vitamin mix tablet as control within a period of one month. The study concluded that *Chlorella* hot water extract has positive effects on breast cancer patients. Those positive effects are a reduction of fatigue, improvement of abdominal symptoms, improvements of dry skin, improvement of hair gloss and improvements of the cold constitution, while the control group did not exhibit any positive effect [67]. Furthermore, most breast cancer patients have a major issue of stress, and *Chlorella* helps in managing the psychological distress in them.

Therefore, the novel studies in the development of new pharmaceutical agents, their pharmacokinetic and metabolism as before clinical trials must be performed to the algal derived biologically active compounds. The clinical studies are then needed for promoting the utilization of algal-derived drugs as potential pharmaceutical agents to fight against the new diseases causing infections.

Algae for aquaculture, animal feeds, and livestock supplements

The rise in global population is projected to reach 8.5 billion by 2030 and 9.8 billion people by 2050 from 7.6 billion people (global population by 2017) according to the 2017 revised UN Department of Economic and Social Affairs (UNDESA) report [68], which pressures the world to find sustainable and sufficient food sources [69]. Animal and fish raising is regarded as one channel toward food security and nutrition. Some people worldwide rely on livestock and fish as sources of proteins and other nutritional components. There is a need for enough quantity, and high-quality feeds, particularly protein-rich feed to sustain animal food production. Unfortunately, conventional animal and fish feed production and availability are affected by climate change and environmental degradation. The promotion of new alternative nutrient-rich and eco-friendly feed sources is a crucial strategy to sustain animal and fish' production.

Algal resources are one of the new sustainable feed resources that can supplement conventional feed due to its excellent nutrient compounds [70]. Algae are considered as a promising novel animal and fish feed with essential components for enhancement of animal growth, nutrients utilization, weight gaining, fertility, and good health [71]. In other words, the algae can produce numerous nutrients and biological active biomolecules content that can fulfill all nutritional and growth criteria for aquaculture and animal feed [72]. Therefore, algal resources are potential renewable sources to complement conventional ingredients in aquaculture and animal feed due to their associated advantages [73]. Algae produce high biomass productivity compared to other feed's sources, high-quality contents such as high proteins, polyunsaturated fatty acids, vitamins, minerals, and pigments sources. Besides that, there are more health benefits other than nutrition such as immune defense, pharmacological, and biological activities including antioxidant, anti-inflammatory, etc.

For instance, Spirulina and/or *Chlorella* intake, as animal feed, has exhibited the improvement in animal health and productivity due to its nutrient-rich and bioactive compounds content with several biological functions [72,74]. Tibbetts, Mann and Dumas [72] highlighted that the biochemical (nutritional and bio-functional) composition profiles of *Chlorella vulgaris* are essential for aquaculture and animal feed. Spirulina is widely used in feed supplements due to its excellent nutrient compounds and digestibility because it does not contain cellulose in its cell wall and it has a small amount of carbohydrate [40].

The improvement of aquaculture and animal feeding strategy with algal resources will enrich the quality and safety of animal-derived foods due to their therapeutic effects over and above nutritional effects [75]. Ample integration of algal-derived feed and phagocytes will promote immune stimulants for Aquaculture Health Management and sustainability [76, 77]. Algal-derived feed can act as immune stimulants due to their several components with various health benefits including polyphenols, polypeptides, and alkaloids. These new approaches in aquaculture and hatchery will contribute to the replacement of traditional practices mainly based on the utilization of animal wastes, antibiotics, and other antimicrobial agents (Figure 6). Moreover, the microalgae

cultivation is a promising process to treat the aquaculture wastewater and micro algal biomass production; thus, in turn, may be used as feed [78].

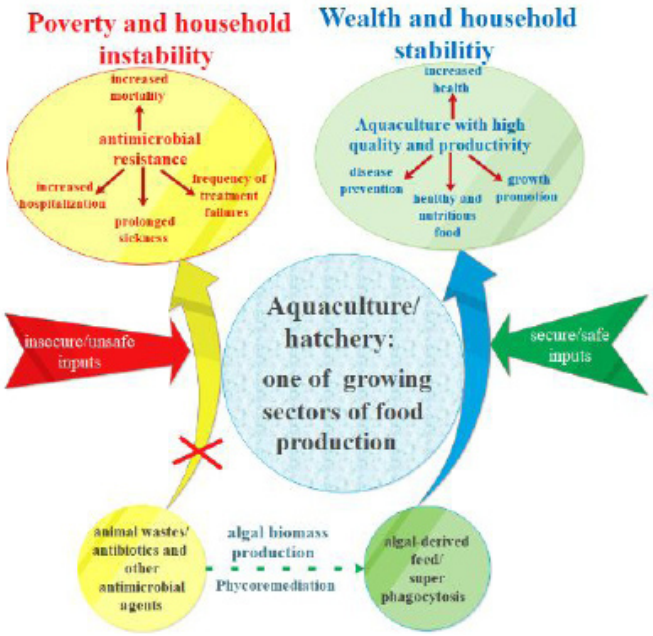

Figure 6: Novel alternatives for aquaculture/hatchery safety and sustainability

Several works revealed that Spirulina feed supplement in poultry reduces the cholesterol of egg yolk and increases the yolk color due to carotenoid accumulation [79]. It will improve the feed quality that will, in turn, lead to the accumulation of essential nutrients in animal meats. In case the animals are fed an unbalanced nutrient diet, for example, starchy feed, they get fat, but the derived meat does not contain essential nutrients needed by the human body. The utilization of algal resources in aquaculture and animal feeds is not new, because it started in 1910 by Allen and Nelson who cultivated *Chlorella* sp. for aquaculture purpose [80]. The utilization of algae in aquaculture and animal feed can also be linked to the eradication of antibiotic resistance. The utilization of antibiotics as infection preventers and growth factors is one cause of antibiotic resistance, where humans can interact with their effects through the food chain.

The macro algae, also known as seaweed, are a source of sulfated polysaccharides that help animals to be healthier. The utilization of seaweeds animal feed is not only regarded as the availability of feeds, it has been proven that it can also reduce the amount of methane released by an animal, but more in-depth researches are necessary to elucidate the mechanism governing the mitigation of ruminal methane production and seaweeds as feed ingredients [81]. For example, one scientific study conducted in Australia reported that 2 percent of *Asparagopsis Taxiformis* (red algae) of the cow's diet was effective in reducing cows' methane emissions by 99 percent [82]. The utilization of algal resources as feed will also contribute to environmental protection by reducing gas emissions because livestock is also responsible for some percentage of all green gas emissions each year [83]. Utilization of algal-derived feed is an alternative that can be used to keep the animal and fish healthy; thus, lead to a reduction in the number of antibiotics to be added to the feed. Therefore, there is a necessity for new scientific studies to prove the replacement of antibiotics with algal derived feeds. The complete replacement of the use of antibiotics by the use of algal resources as feed and prophylactic grow factor can be a promising way to eradicate antibiotic resistance.

Algae for waste and wastewater treatment, bioenergy, and industrial feedstock

Today's global population growth leads to high consumption accompanied by wastes production, depletion of natural resources, environmental degradation [84], and call for a quick change for sustainable progress. The increase of global population has also implicated the tremendous increase in the transportation fleet worldwide and petroleum as a primary energy source is depleting [85]. Climate changes such as global warming are the environmental issue associated with fossil fuel utilization; where the burning of fossil fuels raises the atmospheric carbon dioxide [86]. Therefore, biological carbon sequestration is a new algal resources-based technology, which is regarded as most promising, cost-effective and eco-friendly means of significantly reducing CO_2, and other green gases (including NO_X, SO_X) emissions in the energy industry [14,85-88]. Algal derived biofuels production is the most promising and environmentally friendly energy production because algal resources are cultivated and harvested all year round by combining different cultivation modes, which make algal resources ubiquitous and sustainable feedstock. This mode of alternation could ensure the industries more security of supply of feedstocks. Algal biomass feedstock can be converted into a broad range of algal-derived products, including biofuels and other high valued products. Therefore, several industrial fields are urged to explore algal resources as sustainable and environmentally friendly feedstock [89,90].

Algal resources are regarded as renewable sources of biofuels due to the potential of substantial lipid accumulation [91]. For instance, *Botryococcus* sp. is well-known for the potential for significant lipid accumulation from wastewater [92], where 85% of *Botryococcus braunii* dry weight can be long-chain hydrocarbons. Subsequently, under eco-friendly technology, algal oils are converted into some biofuels such as bio-diesel, bio-hydrogen, and bio-methane [90].

Recent studies have revealed that algal bioenergy production is becoming more economical and eco-friendly due to the new mode of cultivation in different types of wastes and wastewater [92,93]. The algae cultivation using nutrients from wastes and wastewater is one mode of bioremediation, known as phycoremediation of both organic and inorganic pollutants [91,94-96]. For instance, Ganeshkumar, Subashchandrabose, Dharmarajan, Venkateswarlu, Naidu and Megharaj [97] investigated the efficiency in nutrient removal and lipid production by using *Chlorella sp*. grown in mixed wastewater from piggery and winery; the results showed that a mixed piggery and winery wastewater is a cost-effective approach for bioremediation and algal biomass production with a high amount of biofuel yield [97]. In this case, algal resources play a dual role, which is energy production coupled with bioremediation, and vice-versa [91,95,96]. Contrary to fossil fuel production, which is one cause of climate change and environmental problems such as air pollution that is harmful to both public health and ecosystem.

The integration of algae and bioenergy carbon capture and storage is one good example of promising new technology for global sustainability and sustainable algal biomass production as algal resources exploitation [98]. The Bioenergy Carbon Capture and Storage (BECCS), as a promising negative-emissions approach, but still requires the arable land and freshwater and can be unviable and cause competition with food production. The reason why, Beal, Archibald, Huntley, Greene and Johnson [98] proposed and conducted a study on integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) by replacing soy cropland with eucalyptus forests used for BECCS that provides marine algae with carbon dioxide, heat, and electricity. The results from Beal, Archibald, Huntley, Greene and Johnson [98] revealed that the integrated system on 2800-ha facility, without increasing freshwater, produced as much high-quality protein as soy; also the system generated additional economically benefits, which are 61.5 TJ of electricity while sequestering 29,600 t of carbon dioxide per year [98].

It is evident that human activities will continue dramatically to increase with global population growth [99]. Human activities, including industrialization, are the main cause of environmental degradation [87]. Therefore, there is urgently a need for promoting environmentally friendly and cost-effective technologies for wastes and wastewater treatment for environmental sustainability. Wastewater is another current environmental sustainability issue but is getting a promising solution, for its capacity to harbor a large number of algae. The nutrients in waste and wastewater are a suitable raw material for algal biomass and production of high-value products [100], while at the same time the algae can remove pollutants in water bodies, which is a crucial role in environmental bioremediation. Algae have proven potential in assimilating, for their survival, a significant amount of nutrients that would cause eutrophication in water bodies and carry out a wide task in the treatment of wastewater such as removal of other pollutants like heavy metals, Chemicals, among others from agro-industrial, pharmaceutical, and textile dye wastewaters [101].

Although chemical and physical based technologies have been widely used to remove nutrients and treat wastewater in general, they are highly energy intensive and consume large amounts of chemicals, making them costly and less environmentally friendly processes [102]. However, algae-based technologies potentially treat wastewaters by removing nutrients in an inexpensive and environmentally friendly way with added resource recovery, recycling, and feedstock production as added benefits [103]. Mainly, this is a thriving technology, on the one hand, because microalgae biomass produced after treatment is of great value as it can be used for biofuels, fertilizers, and pharmaceutical production [104]. On the other hand, it reduces energy use because when integrated into the conventional activated sludge system, the algae-bacteria symbiosis replace the aeration phase which generally cost more than 60% of total energy spent in wastewater treatment [105]. Through photosynthesis, algae provide the oxygen needed by bacteria to biodegrade organic pollutants and capture CO_2 released by the bacterial activity, which also reduces the carbon footprint.

Algal resources can naturally grow in waterbodies due to the presence of various nutrients and can form algal blooms in eutrophic water bodies [106] causing environmental sustainability issues. Such algal bloom is a threat to ecosystem functioning in cases it is not exploited for other purposes [107]. Algal resources exploitation will strengthen mitigation of eutrophication. In other words, the use of algal resources exploitation can hasten the removal of excess nutrients into water bodies to mitigate eutrophication.

Algae for bio-fertilizers and agriculture

Safe and sustainable agriculture is among the priorities to achieve food security and nutrition, and environmental sustainability. Besides crop production, agricultural practices are associated with ecosystem services including water quality, soil quality, nutrient cycling, and biodiversity conservation [108]. Unsustainable agricultural practices, such as deforestation, are among the leading causes of the negative environment and ecosystem problems including soil erosion and degradation, and pollution [109]. In other words, ecosystem services and agricultural practices are concomitant in some ways because the ecosystem services also affect agricultural crop production. In turn, environmental degradation affects crops production negatively. In the case of agriculture practices are not handled by green technology; they are inevitably threats to environmental sustainability.

There will be increasing pressure on the world to provide enough goods and services to the increasing population [42,69]. Food security and nutrition, and human well-being are among the basic needs to satisfy the global human quality of life [110].

Algal resources provide sustainable feedstocks that are useful in sustainable agriculture and industry [111]. Byproducts from algal biofuels production can also be used in agriculture as bio-fertilizers and feeds [69]. New technologies of large-scale algae cultivation by using wastewater as a source of the nutrient without requiring arable land and fresh water are considered as a promising approach to environmental sustainability. These new technologies for algal biomass production can be used as a bioremediation approach for removing and recycling nutrients from wastewater into algae-based bio-fertilizers [112]. Algal biomass enhances soil fertility as a bio-fertilizer source by improving soil phyco-chemical characteristics including mineral nutrient enhancement [90]. Furthermore, treated water from wastewater treatment can be utilized in agriculture for irrigation. Algae can also produce Aminolevulinic Acid (ALA) that has many applications in different fields including agriculture as a natural herbicide, insecticide, and a growth-promoting factor for plants [113,114].

Conclusion

The algal derived resources synthesize broad nutritional and bio-functional compounds with several applications in various industrial fields for sustainable development. Algal derived resources, as sustainable resources, should be optimally exploited for resolving global challenges including human pathogens [115] and food security and nutrition. The exploitation of algal resources for resolving the global burdening health challenges need to urgently increase willingness in innovation and technology, as well as the educational way for more understanding of potentials of algal-derived products and eradication of negative connotation toward their utilization, especially in developing countries where most burdening challenges are still at high levels.

Future Perspectives

Algal derived foods, and food additives can be effective and adequate natural products to enrich human nutrient-rich health foods if is fully exploited and integrated into food security and nutrition, especially for the poorest population that lacks nutrient-rich food and dietary diversity, thus leading to malnutrition and food-induced diseases. Enriched food will promote body self-protection and self-healing capacities leading to a healthy life.

This review suggests that agencies in charge of algal exploitation should be established, in each country worldwide, for assurance of full exploitation and safety services. Notably, the developing countries should provide a budget for the exploitation of algal resources in several industrial sectors including food, feed, agriculture and aquaculture, pharmaceutical, environment management, and bioenergy. The integration of algal exploitation in those areas will play pivotal roles in solving the food, energy, environmental crisis prevailing in the world, particularly in developing countries. Besides human health benefits, algal resources play a role in animal and fish feeds, as well as environmental bioremediation. Several industries likely consider algal resources as ubiquitous, sustainable, and affordable feedstock and they are promoting related research and development for production efficiency and cost-effective.

Availability of such feedstock will play a significant role in the industries' development. The various industries also need to partner among them for the full exploitation and take the advantages of the benefits of algal-derived byproduct. This approach is a key strategy for the transformation of algal resources into useful assets and to bring algal resources into the human quality of life arena. In this line, researchers, engineers, and stakeholders from various fields have to form alliances to find sustainable solutions to the current world most pressing health challenges. That collaboration will promote the mutual sharing of knowledge in algal resources exploitation for green growth and sustainable development.

Even though algal resources have many advantages; they also have some drawbacks. Some species can produce biogenic and non-biogenic toxins [69]. Therefore, the algal species and production related technology should be selected based on end products and the targeted application as depicted in (Figure 4). Some regulatory standard including quality standards should be established and monitored to prevent any incident that may be caused by algal resources exploitation.

Highlights

- Algal resources are prominent sustainable resources for broad range applications.
- Applications of Algae-derived products are the resolution of global pressing health challenges.
- Algal resources inputs that can contribute to the achievement of a green economy and sustainable development.
- Amply exploitation of algal resources contributes to the potential change in diet and production.
- Phycoremediation is among novel technology that can contribute to environmental sustainability.

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