UMT PRESS

Planetary Sustainability
Journal Homepage: https://planetsust.umt.edu.my
eISSN: 3009-0105
DOI: http://doi.org/10.46754/ps.2023.07.001

ALGAE AND SUSTAINABILITY

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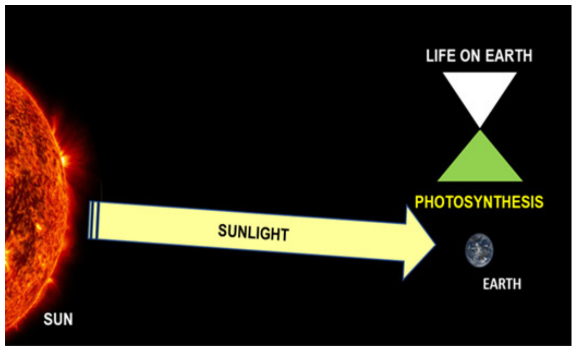
HIGHLIGHTS

- Sustainability of life on Earth is linked to photosynthesis and the Sun.
- Phytoplankton and higher plants are the source of all food.
- Climate change is inevitable but managing anthropogenic impacts is vital.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article History:
Received 5 June 2023
Submitted final draft 9 June 2023
Accepted 9 June 2023

Keywords:
Algae, bioproducts, cyanobacteria, microalgae, phytoplankton, sustainability.

ABSTRACT

Algae (phytoplankton and seaweeds) and their plant descendants shaped the Earth's environment over millions of years to make human existence possible. Food ultimately provided by phytoplankton supports nearly all aquatic animal life, and algae influence key phenomena underpinning the sustainability of life. The natural contributions of algae to a sustainable existence can be augmented through human effort to counter some of the adverse impacts of human activity on climate and the biosphere. As discussed in this article, algae have the potential to sustainable supply food, feed, fuels, other renewable chemicals and materials. They can be used to renewably clean up the environment.

Introduction

This article is about the potential of algae to contribute to a sustainable society. Algae are primitive plants ranging in size from microscopic (microalgae) to giant seaweeds or macroalgae. Like higher plants, algae use water, carbon dioxide, and sunlight to photosynthesize, producing algal biomass and releasing oxygen in the process. Algae colonize mostly aquatic habitats, including oceans, lakes, and rivers. In addition to algae, waterbodies commonly harbor photosynthesizing blue-green bacteria or cyanobacteria. For the purpose of this article, the algae and cyanobacteria are synonymous. The microscopic algae, cyanobacteria, and some other related microorganisms are also collectively known as phytoplankton. The latter typically impart green and blue-green colors to waterbodies but some species have an orange-red color, as in "red tides". Phytoplankton (Sahoo & Seckbach, 2015; Necchi, 2016; Cristóbal *et al.,* 2020), as well as seaweeds (Pereira & Neto, 2015; Vis & Necchi Jr., 2021), comprise a great diversity of species.

Algae are sources and potential sources of foods, feeds, bioactives, cosmetics, bioplastics, and diverse other products (Borowitzka, 1992; Borowitzka, 1995; Shimizu, 2000; Gallardo-Rodríguez *et al.,* 2012; Borowitzka, 2013; Bux & Chisti, 2016; Alves *et al.,* 2018; Chisti, 2018; Chojnacka *et al.,* 2018; Kim *et al.,* 2018). Although algae are often useful, species causing economic harm and disease also exist (Garcia Camacho *et al.,* 2007; Gallardo-Rodríguez *et al.,* 2012; Chisti, 2018). Toxic algae cause mass die-offs of fish, aquatic birds, and other wildlife. Inadvertent consumption of toxic algae causes illness and occasional deaths.

Although microalgae photosynthesize in the same way as most land plants, they tend to have a higher biomass productivity compared to plants (Chisti, 2010a; Chisti, 2019) and therefore are superior to plants for producing food, feed, fuel, and other biochemicals. In contrast with microalgae, the biomass productivity of seaweeds is comparable to that of land plants (Chisti, 2019). Compared with land plants, growing microalgae requires more nitrogen and phosphorous on an equal dry mass basis (Chisti, 2019), limiting their usefulness. Limitations of nitrogen, phosphorous, and other trace nutrients in most natural waterbodies prevent their clogging up with algae.

What is Sustainability?

A clear understanding of sustainability and the extent to which it is achievable is important. There is no such thing as forever sustainability. From the 'Big Bang' some 13.8 billion years ago to today's Universe, nothing has been infinite or sustainable in the absolute sense. Life on Earth exists because of the Sun, a star that formed some 4.6 billion years ago. The Sun is already nearly halfway to its inevitable burnout some 5 billion years from now. Life on Earth will perish much earlier than this as the Sun progresses through its slow demise.

Sustainability is not about preserving the Earth per se, nor is it about simply sustaining life or a primitive human existence. Sustainability is about a fulfilling life for all humans for as long as possible while minimizing our impact on Earth. It is about preventing human activity, or anthropogenic phenomena, from making the Earth uninhabitable by us and the other lifeforms earlier than dictated by nature. Natural phenomena, both physical and lifeforms-driven, have, over millions of years, unquestionably shaped the Earth's environment and will continue to do so. Earth is a changing ecosystem, although the pace of change during much of its existence has been slow, enabling life to adapt.

Life has existed on Earth for some 3.7 billion years, which is nearly 80% of Earth's existence (around 4.54 billion years) but modern humans (*Homo sapiens*) have been around for only the last 300,000 years, a mere 0.008% of the Earth's existence. Algae have had a big role in making human existence possible and continue to be a key factor in sustaining life on Earth (Chisti, 2018). Cyanobacteria and microalgae are among the oldest lifeforms, evolving in an era when the primitive atmosphere had a lot more carbon dioxide than it does today but much less oxygen.

Over the years, phytoplankton photosynthesis enriched the atmosphere with oxygen and removed carbon dioxide, creating a breathable atmosphere that could support higher animal life. Some of the freshwater microalgae migrated from water to land, evolving into modern land plants. Algae and their descendants converted the atmospheric carbon into biomass. As the biomass died and was buried by natural processes, it formed the carbon-rich peat, coal, petroleum, and natural gas, essentially sequestering the carbon forever. Humans evolved, and for thousands of years had barely any impact on the accumulated carbon until the dawn of the Industrial Revolution, beginning roughly 200 years ago, around 1750. Since then, accumulated carbon has been extracted at an accelerating pace and burnt for energy. Carbon removed over millions of years by lifeforms is now being released back into the atmosphere. Disruption of carbon flows through human activity is the cause of self-accelerating climate change. Energy from fossil fuels did undoubtedly enhance societal wealth, but climate change now taking place portends to nullify the earlier economic gains. Climate change may not eliminate life on Earth, but it will alter the environment to something that is unlikely to sustain human life as we know it. An irreversible degradation of the biosphere, poverty and social havoc, and unmanageable epidemics are some of the inevitable outcomes of a changing climate.

Algae continue to remove carbon dioxide from the environment, and the natural fossilization of carbon continues but the anthropogenic release of the accumulated carbon through burning far exceeds the combined ability of algae, plants, and other natural processes to remove it. Hence, the increasing concentration of carbon dioxide in the atmosphere and the resulting impact on climate.

From a human perspective, sustainability has three equally important dimensions: Environmental, social, and economic (Gavrilescu & Chisti, 2005). The biosphere, the small zone of the Earth's atmosphere, and the surface that is inhabited by life, may be sustainable with a sustainable environment but a sustainable society is impossible to achieve without social and economic sustainability. A holistically sustainable Earth could assure the survival of a stable human society and the biosphere. Prevention of too rapid a climate change and preservation of ecosystems and habitats are about a sustainable biosphere, one that changes so slowly that life continues to adapt to change for as long as possible.

Routes to Sustainability

Sustainability Requires Limits to the Human Population

Life cannot exist without impacting the environment. Indeed, the oxygen-rich environment of today attests to life's catastrophic impact on Earth (see What is Sustainability? section). As a rule, the environmental impact of a population is in direct proportion to its size, and the demand for resources increases with population size, no matter how resource-efficient the population is. Earth has a finite carrying capacity for resource-intensive humans. All lifeforms need resources, and competition by humans inevitably means less of everything for the other species. Habitat loss, climate change, and the use of chemicals and materials with adverse ecological impact result in human-driven loss of species with observable as well as unforeseen catastrophic consequences for all life, including human life. Until now, an increasing population has been supported by our ability to influence nature — the creation of ecological imbalances by diverting resources (water, land, forests) for our exclusive use, including a gross disruption of the natural carbon cycle for energy and food.

The existing human population is probably already well beyond the Earth's carrying capacity. The human population expanded first because of the invention of agriculture (Chisti, 2010b) but sustaining a really large population became possible only after the Industrial Revolution. Beginning around the 1750s, population growth and enhanced well-being were driven by the accelerating use of fossil energy with the accompanying release of carbon dioxide. The Earth's population in 1750 was around 814 million. In 1500, the population was around 461 million. Thus, the population grew by around 1.8-fold in the 250 years immediately prior to the beginning of the Industrial Revolution. In the next 250 years, that is between 1750 and 2000, the population expanded to 6.114 billion, a 7.5-fold increase. Production of food (crops, animals, fertilizers, fuel for agriculture and transport) and provision of resources for an adequate well-being of a rapidly increasing population would not have been possible without fossil energy. The consequences of burning fossil fuels were soon apparent, but they were denied until ignoring them was no longer possible.

Animals raised for meat and dairy contribute to climate change. For example, in 2022, around a billion head of cattle, a billion sheep, and more than 0.5 billion pigs were raised for food. There is a need to reduce the environmental impact of food production by changing not only the production methods but also what we eat. Foods based on plants, including algae may provide some reprieve from the adverse impact of animal-based foods but only if the demand for food ceases to grow limitlessly. Therefore, the human population must have limits.

Other Routes to Sustainability

A sustainable society must have a sustainable supply of food, water, and energy (Chisti, 2010b). Therefore, sustainable agriculture and aquaculture are necessary. The carbon footprint of food production must be reduced through changes in agricultural practices. The latter include the use of renewable energy, sustainable methods of production of crops and animals, and the use of biological alternatives to nitrogen fertilizers (Chisti, 2010b). Nitrogen-fixing cyanobacteria, symbiotic rhizobacteria, and other microorganisms capable of converting atmospheric dinitrogen to biologically assimilable forms (Palamae *et al.,* 2020) will have a role in making agriculture sustainable. Without the nitrogen fertilizers obtained currently via the energy-intensive Haber-Bosch process, the existing population cannot be supported.

Replacement of every carbon-emitting process with a carbon-neutral alternative is unlikely to be possible (Chisti, 2010b). Therefore, methods need to be also developed to affordably sequester the carbon dioxide that has already accumulated and that will continue to be emitted to some level in any future sustainable economy (Chisti, 2010b). The use of carbon-neutral renewable energy captured from sunlight through biochemical as well as nonbiological processes for agriculture and other needs, is expected to have a major role in arresting climate change. Prevention of a net carbon release may allow natural phenomena to gradually eliminate the accumulated atmospheric carbon dioxide, but human intervention may be required to speed up the natural processes. Restoration of forests and other natural habitats has a clear potential to sequester the atmospheric carbon in the biomass and soils. Any future algae-based carbon-neutral processes for fuels and materials are unlikely to remove the accumulated carbon dioxide but could slow its build-up. Algae-based sequestering methods have been suggested (Chisti, 2010b) but none have been shown to be practicable. Algal biochar as a sequestration method is a nonstarter, as explained in Algae for Sustainable Agriculture section. Algae do have the potential to enhance the sustainability of agriculture (Algae for Sustainable Agriculture section) and aquaculture (Algae for Sustainable Aquaculture section).

Certain algae (the coccolithophores) are capable of absorbing atmospheric carbon dioxide and removing it essentially permanently from circulation in the form of calcite rock (limestone, chalk, or calcium carbonate deposits). Carbon is sequestered in the skeletal remains that sink to the sea floor once the cells die. Coccolithophores are the major calcite producers in the oceans (Chisti, 2018). These algae dump nearly 1.4 million tons of calcite a year on the ocean floors, removing around 61.6 million tons of carbon dioxide but this removal represents a mere 0.003% of the carbon dioxide released each year by burning around 8 billion tons of coal. Climate change cannot be prevented unless we substantially reduce consumption of fossil energy.

Algae for Sustainable Aquaculture

Aquaculture is the farming of seafood. Supply of wild-caught seafood is limited and not sustainable, hence the need to rely increasingly on aquaculture. Already, nearly 50% of seafood consumed is grown via aquaculture. Aquaculture feeds contain large amounts of fishmeal and fish oil from wild-caught resources as essential ingredients. Fishmeal is a source of the necessary amino acids and other essential chemicals required by fish. Fish oil provides mainly certain long-chain polyunsaturated fatty acids [e.g., the omega-3 fatty acids DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid)] that are not found in vegetable oils. This reliance on a wild resource is not sustainable, hence, the need for more sustainably produced aquaculture feeds.

In nature, aquatic animal life exists because of algae. Algae sustain the tiniest of aquatic animals as well as the largest ones, directly or indirectly, through the food chain. The same role is played by descendants of algae on land. Microalgal biomass produced cheaply and in quantity is potentially a sustainable alternative to wild-caught fish meal and oil for use in aquaculture feeds (Shah *et al.,* 2018; Nagappan *et al.,* 2021; Ahmad *et al.,* 2022; Chi *et al.,* 2022). In addition, palatable food made directly using algal biomass (see Algae for Food and Feed section) may provide all the nutrients currently obtained through the consumption of aquatic animals, hence, potentially reducing the need for both wild fisheries as well as aquaculture.

Microalgae and other microorganisms grown in the dark on organic carbon (heterotrophic growth) can also be used to produce the polyunsaturated fatty acids required in aquaculture feeds (Leyton, 2021; Chi *et al.,* 2022). Furthermore, fatty acids such as DHA and EPA can now be produced using genetically engineered terrestrial crops (Chisti, 2018; Chi *et al.,* 2022).

Algae for Sustainable Agriculture

Naturally occurring algal biomass contributes to soil fertility and may be produced as commercial biofertilizers and soil conditioners (Mutale-Joan *et al.,* 2022; Ghosh *et al.,* 2022). Certain cyanobacteria and other microbes may be used as sources of natural nitrogen fertilizers (see Other Routes to Sustainability section). In addition, biomass may be applied to soils also as biochar. Biochar or charcoal made by pyrolytic treatment of biomass, including algal biomass, applied to soil has been shown to enhance crop productivity (Allohverdi *et al.,* 2021; Schmidt *et al.,* 2021). Biochar can also sequester carbon in the soil for relatively long periods. Although algal biomass can be used to produce biochar (Bird *et al.,* 2011; Roberts *et al.,* 2015; Yu *et al.,* 2017), algal biochar cannot be economically applied to land because of the high cost of the biomass used in making it and because barely any useable heat is recovered by pyrolysis of the water-laden biomass. Algal biochar for carbon sequestration is neither affordable nor rational, considering the huge quantities (around 8 billion tons per year on average over the last 10 years) of naturally produced biochar in the form of coal being burnt annually.

Microalgae are known to produce plant biostimulants, compounds that can be used to sustainably enhance the productivity of land crops (Chiaiese *et al.,* 2018; Mutale-Joan *et al.,* 2022). Natural pesticides can be sourced from algae for sustainable crop protection (Costa *et al.,* 2019). As with commercial crops, the large-scale culture of phytoplankton is susceptible to pests and diseases that need to be managed (Molina-Grima *et al.,* 2022).

Algae for Food and Feed

Among phytoplankton, only a few species have been used as food to a limited extent, but there is substantial scope for such use. The cyanobacterium *Arthrospira* (*Spirulina*) has been consumed as human food for thousands of years (Chisti, 2018), and its nutritional characteristics and health benefits are well documented (Gershwin & Belay, 2008). Similarly, commercial seaweed farming is well-established in many countries (Bux & Chisti, 2016; Hurtado *et al.,* 2017; Peñalver *et al.,* 2020), in addition to the collection of biomass from the wild. Seaweeds are used as food and a source of diverse food additives. Seaweeds can also be used in feeds for certain fish species (Vazirzadeh *et al.,* 2022a).

Compared to meat and dairy, microalgae may prove to be a more sustainable source of protein. Phytoplankton grown in nutritionally complete media typically contain 30–50% protein on a dry mass basis (Chisti, 2019). This protein-rich biomass can be used in food and feeds (Kent *et al.,* 2015; Barka & Blecker, 2016; Caporgno & Mathys, 2018; Li & Wu, 2020; Zeng *et al.,* 2022), although possible pretreatments may be required to enhance protein availability. Algal protein is generally of high quality but may require supplementation with some essential amino acids. Seaweeds may also prove to be a nutritionally valuable source of protein (Brien *et al.,* 2022).

Algae as food ingredients have been discussed by others (Vigani *et al.,* 2015; Ścieszka & Klewicka, 2019; Matos *et al.,* 2022; Mendes *et al.,* 2022; Raja *et al.,* 2022). Macroalgae for food is generally a much bigger and diverse market compared to food uses of cyanobacteria and microalgae. This notwithstanding, algal biomass for food is a niche market compared to most other mainstream foods. Methods need to be developed for converting the nutritionally wholesome algal biomass to diverse palatable foods.

Renewable Fuels and Chemicals from Algae

In principle, algae have the potential to provide diverse kinds of renewable biofuels, including bioethanol via hydrolysis of algal starch to sugars followed by fermentation; bioethanol by direct photosynthetic fixation of carbon dioxide and water; biomethane from anaerobic digestion of algal biomass; biodiesel from algal oil; biohydrogen; and others. Production of several type of algal biofuels has been shown to be technically possible but economic viability has eluded them (Chisti, 2007; Chisti, 2010a; Chisti, 2019; Pandey *et al.,* 2019; Bhat *et al.,* 2022).

Algal fuels require sunlight, and therefore, culture devices with large surface areas to capture light; a concentrated supply of carbon dioxide and therefore proximity to its sources; plenty of water, including freshwater; inorganic nutrients, especially nitrogen (nitrate, ammonium, urea) and phosphate. The same nutrients are used in agriculture, and their existing supply is already fully used for growing crops. Nutrients in some wastewater may be recyclable for growing algae for nonfood applications. Fuels and chemicals from renewable algal biomass may be potentially carbon neutral but existing technologies for producing them do not demonstrate this.

Constraints to the commercialization of algal fuels are severe, and questions remain about the real sustainability of such fuels (Chisti, 2013; Chisti, 2018; Chisti, 2019). The energy required to produce some algal and other biofuels may exceed the energy they contain, resulting in a negative energy balance (Chisti, 2010b). A negative energy balance may not necessarily be bad so long as the carbon footprint of the biofuel is smaller than the carbon footprint of the fossil fuel it displaces (Chisti, 2010b). Furthermore, the utility of different energy sources can be quite different, so, equating a megajoule of fossil energy to a megajoule of bioenergy may be flawed (Chisti, 2010b). For example, 8400 kJ worth of food can fuel a person for a day but not the same kilojoules worth of petroleum (Chisti, 2010b). Notwithstanding the sustainability issues, no algal fuels have proven commercially successful (Chisti, 2019).

Commercial viability may be improved by recovering multiple products from a given algal biomass in a biorefinery (Prokop *et al.,* 2015; Laurens *et al.,* 2017; Chandra *et al.,* 2019). This is somewhat analogous to the production of multiple product streams from crude oil in a petroleum refinery. Unfortunately, a biorefinery scheme is often not practicable as the growth process of algal biomass is typically designed to maximize its content of one or two main products, and the other potential products are then present in quantities too small for cost-effective recovery.

Algae for Wastewater Treatment

Humans need fresh water and generate wastewater. With freshwater resources being limited and overused, there is a need to clean and reuse wastewater and minimize the discharge of untreated wastewater into the environment. Biodegradable dissolved carbon compounds are already being removed from wastewater by highly effective nonalgal biological treatment methods but there is a need to remove also the inorganic nutrients such as the dissolved nitrates and phosphate. A major source of the inorganic nutrients is the fertilizers washed off the cropland by rainwater. Removal of these nutrients is possible using photosynthesizing algae (Vazirzadeh *et al.,* 2022b), although only in rural settings where the quantity of water needing treatment is limited and sufficient land is available to site treatment ponds requiring large surface areas to access sunlight.

Algae-aided removal of organic carbon by nonalgal microorganisms is also feasible but depends on sunlight and therefore requires ponds with large surfaces. In such processes, algae enhance the biodegradation of waste by providing photosynthetically generated oxygen that is then used by the nonalgal heterotrophic microbes to oxidize the organic waste.

Environmental remediation aspects of microalgae and cyanobacteria have been extensively discussed in the literature (Sharma *et al.,* 2014; Singh *et al.,* 2015; Whitton *et al.,* 2015; Pathak *et al.,* 2018; Roy *et al.,* 2022). Applications are mostly niche, compared with the other well-established microbial processes such as anaerobic digestion (Valijanian *et al.,* 2018) and activated-sludge-based treatment of wastewater.

Conclusion

The action of algae made human evolution possible, and life on Earth cannot be sustained without the natural contributions of algae and other photosynthesizing species. Algae have the potential to be used in the sustainable production of goods and services but their capacity is limited by several important factors (Chisti, 2013; Chisti, 2019), including a lack of large quantities of essential nutrients such as nitrates and phosphates needed to grow them; a lack of suitably located point sources of concentrated carbon dioxide required by the algae; the need for freely available natural light and the propensity of dense algal cultures to limit their own access to light; the need for large surface areas to capture light; and the requirement for significant quantities for freshwater.

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