



Algae and their potential for a future bioeconomy, landless food production, and the socio-economic impact of an algae industry

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Abstract Despite being a comparatively new branch of agriculture, algae production is often considered to be a solution to many food security-related problems, such as land scarcity, climate change, inefficient and unsustainable fertilizer usage, as well as associated nutrient leakage and water pollution. Algae can be cultivated independent of arable land and, especially in the case of many microalgae, produce oil- and/or protein-rich biomass with spatial efficiency which far exceeds that of terrestrial plants. Nevertheless, algae and algae-derived products are almost exclusively produced for high-value, low-volume markets and are far from being able to compete with cheap commodities such as plant-based proteins or fossil fuel. High investment and production costs are considered the main reason for this, but a lack of economic incentives for sustainable production and CO₂ mitigation should not be overlooked. The development of new production technologies; the monetization of ecosystem services, such as water treatment, CO₂ sequestration, and nutrient recycling; as well as the simultaneous production and marketing of “high-value, low-volume” and “low-value, high-volume” products from the same algal biomass are the most promising ways forward. A sustainable “algae industry” could be an integral part of the future bioeconomy, enabling more

resource-efficient food and fuel production and creating new products, companies, and jobs.

Keywords Microalgae · Seaweed · Biomass processing · Circular economy · Landless food · Biofuel · Wastewater · Nutrients · Climate change · Ecosystem services

Algae production: history, present, and future

Algae are a polyphyletic group of organisms from four different biological kingdoms: Bacteria, Plantae, Chromista, and Protozoa. Around 44,000 species have been scientifically described, but the real number, though dependent on which definition of “algae” is used, will be much higher, with some estimates being as high as a million different species (Guiry 2012). As photoautotroph organisms, algae are the starting point of most food webs in aquatic ecosystems. The biomass productivity of many algal species is much higher compared to that of terrestrial plants, and they can be efficiently cultivated without antibiotics and pesticides in fresh or sea water. These factors, as well as their high content of vitamins, polyunsaturated fatty acids, and other healthy compounds, have led to increasing consumer demand and commercial interest in algae production during the last decades.

Seaweeds have been used as food and medicine for at least 14,000 years and possibly even played an important role in the peopling of the Americas (Erlandson et al. 2007). First farming activities of seaweeds in East Asia date back at least to 1640 (Pulz and Gross 2004), though possibly much longer (Ferdouse et al. 2018). Consumption

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of microalgae on the other hand has historically been rare. The only commonly cited examples are the harvesting of naturally occurring *Spirulina*, a genus of cyanobacteria, by the Aztec people in the valley of Mexico and the Kanembu people around Lake Chad (Ahsan et al. 2008). The large-scale cultivation of microalgae and seaweeds is a very new branch of aquaculture, dating back only to the middle of the twentieth century, when the global industrial production of algae was near to “zero” tons. The first commercial cultivation of a microalgae was that of *Chlorella vulgaris*, which started in Japan, in the 1960s (Mobin and Alam 2017). In 2004, one estimate put the global production of microalgae at around 5000 tons (dry weight) and US\$ 1.25 billion per year (Pulz and Gross 2004). The production is likely to have increased a lot since then; however, it is surprisingly hard to find reliable data on this. Seaweed production has also increased rapidly: the FAO estimates that the global production more than doubled, from 14.7 million tons (wet weight) in 2005 to 30.4 million tons in 2015, which accounts for a market of roughly US\$ 6 billion (Ferdouse et al. 2018; Camia et al. 2018). Compared to the global agricultural production of roughly 1.6 trillion tons, this is still an extremely small amount (Buschmann et al. 2017).

Of the 220 species of seaweed that are commercially used, most are farmed offshore, in marine environments, while only about 1.1 million tons are harvested in the wild—a number that has been stagnant in recent years (Ferdouse et al. 2018). Most of the produced seaweed is either used as human food (roughly 47%) or for the production of hydrocolloids (over 50%), such as agar, carrageenan, and alginate (Buschmann et al. 2017). The productivity of different seaweeds in offshore farms in Japan lies between 1.3 kg/m² for *Laminaria angustata* and 8.3 kg/m² for *Sargassum macrocarpum* and is thus comparable to the productivity of land crops (Notoya 2010). According to estimates by the World Bank (Bjerregaard et al. 2016), 5 million km² of seaweed production area—roughly 0.3% of the ocean surface—would be enough to produce as much biomass as is produced in all of global agriculture annually.

Even though microalgae are spatially more productive than terrestrial plants and macroalgae—*Spirulina*, for example, produces about 10 times more biomass per hectare than high-yielding corn hybrids (Dismukes et al. 2008)—their production is still more expensive, especially due to high initial investment and production costs. For this reason, microalgae production is mainly focused on the

provision of “low-volume, high-value” products, such as β -carotene, astaxanthin, docosahexaenoic acid, docosahexaenoic acid, phycobilin pigments, and algal extracts for use in cosmetics, instead of “high-volume, low-value” products, such as biofuel, food, or feed (Borowitzka 2013). The same goes for seaweeds, which some also view as ideal crops for biofuel production, due to high carbohydrate contents of roughly 50%. With fossil oil prices being as low as they are, there is at the moment little chance of competitiveness. One way of overcoming this problem in the case of microalgae production is either the development of a scalable phototrophic production technology or the development of a convincing biorefinery concept for the multiple use of the algal biomass. Light limitation and technological limits are the most challenging tasks. The other approach is focused on the monetarization of ecosystem services that algae can provide: the cleaning of water, the mitigation of climate change, etc. This approach, though promising, requires significant changes in the legislative set-up of the economic system and is thus highly controversial. In the following passage, we want to delve deeper into these problems and outline a way forward.

The ideal microalgae production system?

An ideal production system for algae cultivation is not focused only on the provision of one product. Instead, it takes advantage of the ecosystem services that algae can provide and extracts several products from the same biomass. This has economic as well as environmental advantages. Today three different production methods are established: open pond systems, photobioreactors, and fermenters. Each technology has its advantages and disadvantages. A decision on which one to choose should be highly dependent on the final product and/or application, the microalgae species, and the production costs. Next to the availability of water (especially for the cultivation of freshwater species) and high solar radiation, labor and energy costs are important factors to bear in mind, since these are major drivers of production costs. It could be argued that an “ideal” production system would favor marine species over freshwater species, since sea water is an unlimited resource, and phototrophic over heterotroph production, since this would bind rather than emit CO₂. However, this would be an oversimplification. Freshwater algae can, for example, be used for wastewater processing or in areas where freshwater is abundant.

Fermentation on the other hand is easily scalable, relatively cheap, and interesting for “refining” organic carbon compounds such as dextrose or acidic acid into biomass which is rich in compounds such as Omega 3 or antioxidants. Also, the CO₂ from fermentation could be used to boost productivity in photobioreactors.

In an ideal production system, the provision of CO₂ as fertilization for photobioreactors should not be a cost factor. Richardson et al. (2010) estimate a price for CO₂ of \$0.0035–0.313/kg of biomass produced. If money was made rather than spent by using CO₂ as fertilizer in algae production, for example, if a CO₂ tax was introduced, this would have a significant impact. However, political and social support for improving the economic conditions for algae production through such means is still lacking (Nhat et al. 2018).

When it comes to photobioreactors, open pond systems are generally less expensive to build and operate. Therefore, for large-scale biomass production at low product cost, closed photobioreactors are usually considered unsuitable (Lundquist et al. 2010). However, closed bioreactors or fermenters are ideal for cultivation of high-quality starter cultures, which are used to inoculate open pond bioreactors. Also, when it comes to high-value products, closed photobioreactors are oftentimes ideal, because they produce more reliably and are less affected by pests than open pond systems. Closed photobioreactors also require more energy for gas exchange, to avoid oxidative stress (Kuenz et al. 2020). However, they can also be more efficiently used for the sequestration of CO₂ from flue gases than open systems.

To help reduce the costs of high-volume, low-value products, derived from algae, a simultaneous production of high-value products from the same biomass seems to be the most promising way forward.

Pigments, such as chlorophyll, carotenoids, or phycobiliproteins, as well as biologically active compounds used for pharmacological applications, can be extracted from algae as byproducts of oil or protein extraction. This could help to offset the high costs of cultivation and harvesting and thus make microalgae-derived biofuel (Bai et al. 2011) or proteins more competitive. However, this extraction method uses chemicals such as methanol and hexane, which could increase the environmental impact.

It is also possible to extract oil from microalgae via hydrothermal liquefaction (HDL). This process, in which algal biomass is heated at around 200–350 °C

and under pressure of 15–20 MPa, has the advantage that it can be used on wet biomass, which saves energy (Fernandez et al. 2018). The byproducts of HDL are organic compounds, some of which are poisonous if released as wastewater. However, it has been shown that anaerobic digestion of these compounds enables efficient methane and thus energy production, which could further reduce the costs of this process—which is especially cost and energy efficient compared to alternatives (Nhat et al. 2018).

Algae and their potential in a future/circular bioeconomy

Since algae production needs not only water and carbon dioxide, but also a range of macronutrients, like nitrogen and phosphorous, it could be the ideal production system to produce biomass from certain waste streams. Considerable amounts of these nutrients are used in agriculture and end up in the sea and lakes, which often results in harmful algal blooms (Michalak et al. 2013). Seaweed farming in deltas, river mouths, or bay areas could not only profit from this resource but also help to reduce the environmental impact of nutrient run-off derived from agricultural activities.

Another question of increasing importance is how to recycle urban waste streams. It is estimated that 68% of the human world population will be living in cities by the year 2050 (United Nations 2018). A potential solution for nutrient recycling under such circumstances could be the urban/vertical farming of algae, potentially indoors, e.g., under greenhouses on rooftops, using closed or semi-closed reactor systems. There are already a few realized concepts, such as the “Algenhaus” in Hamburg, Germany (Abmus et al. 2018), and a lot of theoretical concepts on how to integrate algae farms into modern architecture.

Especially in urban settings, the bioremediation of waste waters is of increasing importance, and it is thus one of the applications of microalgae which have sparked most interest. By using phototrophic algae in the bioremediation process, the energy costs and greenhouse gas emissions of wastewater treatment could be reduced, since biomass would be created, which could be processed to biogas or fuel, and because the oxygen produced by algae could potentially be used to make other processing steps, such as aerobic fermentation, more effective. Vice versa, the CO₂, which is produced in the burning of biogas, could be fed into bioreactors, to

increase algal growth. In addition to producing drinking water and binding nonrenewable nutrients, such as phosphate, and renewable nutrients, such as nitrogen, algae as part of wastewater treatments would thus reduce the environmental impact of this process. A likely downside compared to “conventional” wastewater treatment would be the need for more space. Lundquist et al. (2010) calculate that around 100 ha of open pond bioreactors would suffice to treat the wastewater of 165,000 to 235,000 people. The area for such a wastewater treatment plant/algae farm should not infringe on agricultural land or the living space of urban populations. Figure 1 shows different scenarios (on-shore, off-shore, urban settings, and aquaponics) in which algae cultivation can be practiced, which we discuss in the paragraphs below, and highlights products, as well as ecosystem services, which can be provided in these ways.

Land-based algae farms

Land-based microalgae cultivation should ideally take place on non-arable land. A lot of examples of open pond systems or photobioreactors in arid regions are

available, like the Arava desert (Israel), the Atacama Desert, or the coastal desert of Morocco (SuSeWi 2020). Coastal deserts are excellent locations for the cultivation of marine microalgae, since no freshwater is used, while the sea water that is being used is virtually unlimited. Cultivation of freshwater algae should take place either in urban areas, ideally as part of wastewater treatment, or in humid climate zones, where freshwater is not a limited resource. In such areas, open pond “microfarms” could help to fight malnutrition locally and make farmers independent of increasing prices for arable land and fertilizers (Rahmann et al. 2020).

The options that take up the least space are fermenter systems, which could be used to refine lower value products, like organic C-compounds into high-value products (PUFA, pigments).

Sea-based algae farms

Classical seaweed farms are installed on the coastlines, as sole seaweed farms or as integrated multitrophic farms realizing fish/invertebrate farms in combination with seaweed production at the same place and time.

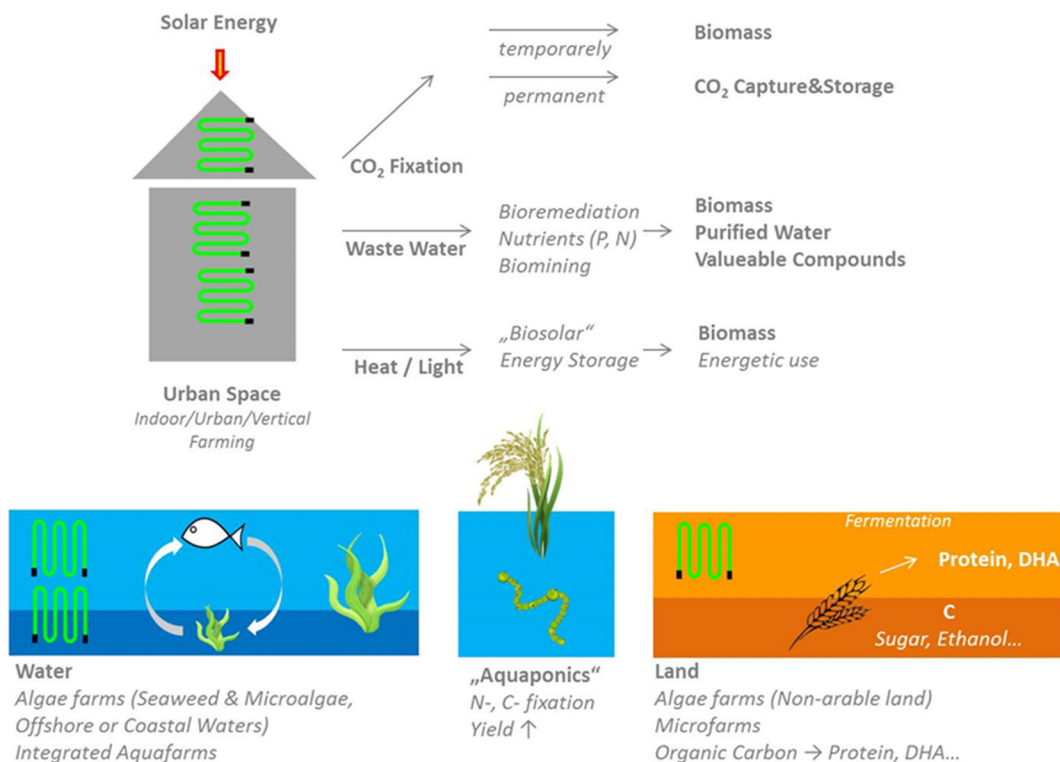


Fig. 1 Potential of algae for a circular bioeconomy, landless food production, and urban farming

This could also help capturing fertilizer run-off from intensive agricultural areas and thus prevent damage to coastal aquatic ecosystems. Another option, offshore farms of seaweed, seems to be too expensive to realize and run, though this might change in the future.

Offshore microalgae farms are part of research projects but still in a very preliminary phase. The idea is to have floating, closed bioreactors, on water surfaces. The OMEGA research program by the NASA, for example, looks into floating, more or less tubular membrane enclosures (Wiley 2013). Advantages of floating microalgae farms, apart from the lack of need for land, are that naturally occurring could provide mixing and the seawater could provide cooling of the photobioreactors.

Special Aquaponic systems based on blue-green algae

Nitrogen-fixing Cyanobacteria (blue-green algae) have been used for a long time as inoculum for rice fields to increase yields (Mishra and Pabbi 2004). Similar Cyanobacteria are the natural symbionts of some legumes and known for their N-fixing potential. These cyanobacteria could fixate nitrogen as macronutrient from the air and recover phosphorous from wastewater simultaneously, which would be an interesting application and an enhancement of the traditional use of these species.

Establishment of an algae industry and its socio-economic impact

The algae industry is no older than 70 years and currently mainly produces extracts for processed foods and other industries, such as cosmetics and medicine. High growth rates in these sectors, as well as new innovations, such as sustainable packaging from seaweed, to replace oil-based plastics, are reason for optimism about the future of algae cultivation. But apart from pure biomass production, there is a huge potential for developing a sustainable algae industry along the whole value chain, supported by a strong applied research and the valorization of strain collections and genetic resources, as well as patents, new applications, technologies, and product developments. This could be an important step towards developing a bioeconomy, while creating new education possibilities, innovations, services, and jobs. The following five points should be the strategic focus points

for developing such an algal bioeconomy and promoting growth in the sector:

1. Basic and applied research center(s)

Focused mainly on applicative research, product development, technological development, process development, publications, and commercialization of patents

2. Commercial (local) strain collections

Knowledge collection and commercialization of local strains and biological/genetical resources. Also, a means of biological monitoring of environmental changes or natural conservation

3. Education (schools and universities)

New study subjects, e.g., “Algae Biotechnology”

4. Support of startup companies

Creation of a strong network to develop promising go-to the market strategies

5. Financing

Development of tools to finance projects (“algae fund”) and research

Asian producers of microalgae and seaweed are currently the main drivers of growth. The number of algae-producing companies in Europe has grown, but their impact is still low. Algae biomass production in the EU (0.23 Mt, fresh weight) contributed less than 1 % to the global production of 30.4 Mt in 2015 (Camia et al. 2018). However, current EU political priorities favor a transition towards a sustainable economy and therefore also the development of an algae sector, e.g., the EU Bioeconomy Strategy (European Commission 2018), the EU Blue Growth Strategy (EC, 2012), and the European Green Deal. The EU also funds development aid projects related to algae cultivation, for example, a €8 million project to help Kanembu communities in Chad adapt to the impacts of climate change and develop renewable energies, providing technology for more effective cultivation and drying of *Spirulina* (European Union 2020). The work is done mainly by women. Increase of production volumes and quality could generate more jobs and income for them.

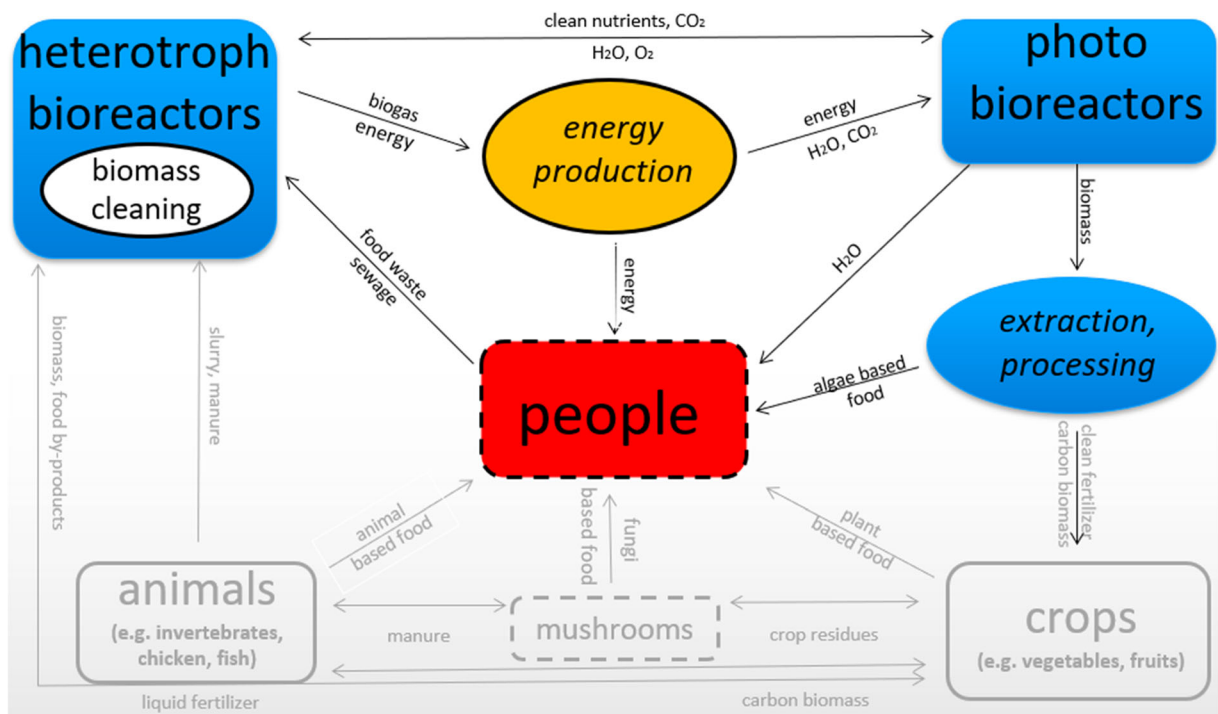


Fig. 2 Flow model of a circular food system, as proposed by the LandLessFood project (Rahmann et al. 2020), with algae production and related elements highlighted

There are many examples of the socio-economic benefit of algae industries in developing countries. The harvesting of *Eucheuma* seaweed in Zanzibar accounts for 7.6% of the islands GDP, and in total, Tanzania's seaweed industry employs 30,000 people (The Fish Site 2020).

Recently in Bali, seaweed farming has received a renewed boom, after having been dialed down, roughly a decade ago. Due to the Corona crisis, the tourist industry has collapsed, and seaweed farming was rediscovered, generating an income of up to 400 USD a month for workers. This is just over half of what people had before pandemic but shows that diversification could help to overcome such crisis (Channel News Asia 2020).

Conclusion

The cultivation of algae can make an important contribution to the food security of future generations, especially in regions of the world where, due to population growth, the available cropland is likely to be insufficient. This is especially true for Africa, where only 458 to 629 m² of cropland will be available per person in 2100 (Rahmann and Grimm 2020). If integrated into the agricultural system

in a circular manner, as depicted in Fig. 2, algae cultivation could decrease nutrient losses and greenhouse gas emissions, as well as provide green energy. For this to become a reality, algae production has to become cheaper, in order to compete with cheap, high-quantity products, such as oil. New technology and upscaling of algae production, as is already happening today, can make an important difference. For algae producers, the valorization of strain collections and genetic resources, as well as patents, new applications, technologies, and product developments, is an important way forward. On a grander scale, however, it is important that governments support research programs on cultivation and processing of algae and introduce legislation which incentivizes sustainable production, while discouraging pollution, for example, through the introduction of a carbon tax or similar measures related to pollution by over-fertilization. Only if externalities which are caused, for example, by the burning of fossil fuels, excessive fertilizer use, or deforestation for food production are reflected in the price of products can sustainable technologies such as algae production become competitive in a relatively short time period.

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