Chapter 35

Socioeconomic Aspects of Third Generation Biofuels

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Abstract

This chapter examines the socioeconomic, environmental, ethical, policy-related, and geopolitical aspects of biofuels, comparing conventional (first and second-generation) biofuels to the third (and fourth) generation of biofuels that are produced by algae. The chapter commences with a review of the basic characteristics of different biofuels, including definitions, production, economics, and challenges. Socioeconomic aspects include land; employment and income; costs and prices; gender and culture; and public acceptance. Issues that algal biofuels largely avoid (or affect differently) include competition for agricultural land; debate between food and fuel; rising food (and commodity) prices; pressures for deforestation; and reduction of biodiversity. Public attitudes are largely governed by emulation of social norms, but the public is not acquainted with algal biofuels well enough to be engaged in such behaviors and research on algal biofuels is lacking. Environmental aspects relate to the atmosphere; greenhouse gas emissions; land and soil; deforestation; ecosystems and biodiversity; water quantity and quality; wastes and recycling; energy; health and safety; aesthetics; and sustainability. Conventional biofuels affect water quality and quantity and have a debatable contribution towards fighting climate change while algal biofuels can reuse wastewater, but may be associated with safety issues. As regards the strenuous relationship of the Global North to the Global South, conventional biofuels have been associated with environmental injustice and affect socioeconomic, ecological,

food, transportation, energy, and even national security. Policies in the European Union, the US, China, India, and Latin America are presented and discussed. The chapter is rounded up with a summary and conclusions.

Keywords: third-generation biofuels, socioeconomic impacts, geopolitics, energy security.

1. Introduction

Biofuels are liquid fuels derived from biomass (Doshi et al., 2016) and they constitute a relatively new type of renewable energy source (Chin et al., 2014). Depending on the feedstock, biofuels are distinguished in generations. The first and second generation of biofuels are produced from edible and inedible plant parts correspondingly. The third generation of biofuels are produced from macro and microalgae, while the fourth generation signifies algae that have been genetically modified for increased energy efficiency.

Contrary to most other renewable energy sources, biofuels offer the possibility of replacing fossil fuels in the transportation sector (Villarreal et al., 2020), which is a major contributor of carbon emissions (Chin et al., 2014). Currently, most automobiles operate on internal combustion engines that run on fossil fuels. While electric mobility likely represents the future of transportation, transitioning to electric vehicles entails financial and technological costs (Doshi et al., 2016). This is where biofuels come in. Since biofuels have combustion properties similar to those of fossil fuels, they require minimal modifications to internal combustion engines (Doshi et al., 2016) and may be supplied by the existing infrastructure (Chin et al., 2014). So, biofuels are a promising and realistic potential substitution fuel for transportation.

Beyond the obvious advantages though, biofuels face skepticism because they are characterized by problems and conflicts (Xi and Long, 2016). Cultivation of their feedstock and production of biofuels has social, economic, and political impacts (Sawyer, 2008). While some conventional biofuels are associated with food versus energy conflicts, biofuels based on algae are produced on an entirely different feedstock that does not compete with food.

So, algal biofuels may well represent the future of biofuels provided their technology evolved and matures.

This chapter examines the socioeconomic and environmental aspects of algal biofuels, balancing them with political and geopolitical concerns. The rest of the chapter is structured as follows: Section 2 defines the different biofuel generations and reviews their characteristics, with Section 2.1 focusing on algal biofuels. Section 3 examines the socioeconomic aspects of algal biofuels, with Section 3.1 focusing on public acceptance issues. Section 4 examines the environmental aspects of algal biofuels, with Section 4.1 focusing on ethical issues. Section 5 examines political and policy aspects of algal biofuels, while Section 5.1 focuses on geopolitical and security issues. Finally, Section 6 rounds up the chapter with discussion and conclusions.

2. Biofuel generations and production

Biofuels are energy sources in liquid (or gaseous) form derived from biomass (Gonzalez, 2018) and constitute a form of renewable energy source that is an important alternative to fossil fuels. This section reviews the generations, products, and challenges of biofuels with an emphasis on algal biofuels.

2.1. Biofuel generations

Contrary to other renewable energy sources like solar and wind power, biofuels require not only a processing facility but also a supply of feedstock (Chin et al., 2014), which in the case of biofuels is provided from biomass. Depending on the type of feedstock used, there are four (so-called) generations of biofuels (Saad et al., 2019; Gonzalez, 2018). Biofuels derived from terrestrial plant feedstock are called conventional biofuels and are further divided to first and second-generation biofuels (Doshi et al., 2016). For first-generation biofuels, edible plant biomass constitutes the feedstock, while for second-generation biofuels, nonedible plant biomass constitutes the feedstock (Chin et al., 2014). Third and fourth-generation biofuels rely on algae and cyanobacteria for their feedstock (Efroymson et al., 2017).

First-generation biofuels are derived from edible parts of the following plants: sugar beet; sugarcane; maize; oil palm; soybean; sweet sorghum (Saad et al., 2019). First-generation biofuels represent 99.85% of the biofuels produced globally and dominate the markets (Gonzalez, 2018), but are considered to have negative impacts on food and water. For second-generation biofuels, the feedstock is inedible (lignocellulosic) crop parts (like stems, leaves, and husks) or waste products (like cake bagasse) of mostly vascular plant biomass, like sugarcane crops residues (bagasse), firewood, switchgrass (Miscanthus sp.), silver grass, forest and plantation residues for biopetrol, and Jatropha sp. (a type of shrub named after the Greek word for physician) (Efroymsonet al., 2017; Correa et al., 2021; Saad et al., 2019; Gonzalez, 2018).

The advent of second-generation biofuels was discussed by Sawyer (2008), who suggested that around 2015 it would become feasible to produce biofuel from generic biomass (cellulose). Despite their promise of alleviating food vs energy conflicts, second-generation biofuels have developed more slowly due to the high capital costs of refining their feedstock and their dependence on subsidies and other economic incentives (Gonzalez, 2018).

Third-generation biofuels are algae-based biofuels that do not compete with food nor land that could be used for food production (Gonzalez, 2018). Algal biofuels do not compete for land or food, can be fed on wastewater, and only need water and sunlight to grow, while some biofuel strains can harness 3% (or more) of the incoming sunlight as opposed to less than 1% by photosynthesis (Gomiero, 2015). Despite their great promise, third-generation biofuels have been the slowest to develop because their feedstock (algae) needs a lot of water, nitrogen, and phosphorus. Algal biofuels also face high costs to comply with current mandates. Fourth-generation biofuels have emerged as a particularly appealing solution using algae that has been modified genetically to maximize yield and minimize costs (Saad et al., 2019).

Bioethanol, biodiesel, biogas, biomethanol, biokerosene, biohydrogen, syngas, and bioethers are alternative terms for biofuels (Saad et al., 2019). Bioethanol and biodiesel are the major types of biofuel, and they are both made from first-generation processes. Bioethanol is a substitute for gasoline, and biodiesel is a substitute for diesel (Correa et al., 2021).

Bioethanol (or biopetrol) is made from carbohydrates (sugars) while biodiesel is made from lipids (fats) (Doshi et al., 2016). First-generation production processes may produce bioethanol (derived from carbohydrates like starch in maize, and sugar in cane); and biodiesel (derived from plant oils in soybean, sunflower, rapeseed/canola oil, and palm oil, mostly in India, China and Southwest Asia) (Gonzalez, 2018; Doshi et al., 2016; Sawyer, 2008). Technical progress has permitted the production of cellulosic ethanol (Sawyer, 2008). Also, bioethanol may be produced from algal carbohydrates while biodiesel from algal oils (Saad et al., 2019).

2.2. Biofuel challenges

Biofuels offer technical, socioeconomic, environmental, and political benefits (Chin et al., 2014) These benefits reportedly include reduction in greenhouse gas emissions; improvement in air quality; job and wealth creation; rural development; and fuel price stability (“Societal Benefits of Biofuels in Europe”, n.d.). Nevertheless, there are also diverse challenges that relate to the development of biofuels and must be addressed, involving the environment, resources, society, and the economy (Xi and Long, 2016).

In particular, biofuels are characterized by technical barriers, and economic, social and environmental debates. These relate to deforestation; loss of biodiversity; haze pollution; increase of carbon emissions (e.g. when land use changes occur); increase of nitrogen and particulate emissions; water usage; energy usage; food vs fuel conflict; rural poverty; and land use conflicts (Chin et al., 2014). Many of these issues affect the social acceptance of biofuels and motivated the move towards the second-generation biofuels, using nonedible vegetable oil as feedstock. It is because of these reasons that algae (third-generation biofuel) have also attracted the interest of researchers.

Issues that the literature has identified, pertaining to conventional (i.e. first and second-generation) biofuels derived from terrestrial biomass include: (1) lower net energy returns; (2) overstated net carbon emission benefits; (3) paradoxically, increased dependence on fossil fuels (instead of more energy independence); and (4) competition with food demand through crop and resource allocation (Doshi et al., 2016).

Current biofuels production systems are mainly first-generation, i.e. based on food crops, so they compete with agricultural land for the production of feedstock (Correa et al., 2021). While second-generation biofuels are not derived from (parts of) plants grown for food, some are derived from plants grown on agricultural land that could be used to cultivate food (Gonzalez, 2018).

Although the biomass left over after the production of biofuels may be used for the production of supplements, animal feed, fertilizers, etc. (Saad et al., 2019), first and second-generation biofuels cannot meet global energy demand in a sustainable way (Villarreal et al., 2020). Thus, third-generation biofuels are considered to play a crucial role in helping achieve long-term climate policy objectives especially in regard to the energy demand of the transportation sector. It is expected that algal biofuels may help overcome the drawbacks that afflicted first and second-generation biofuels (Rösch and Maga, 2012).

2.3. Algal biofuels

Being an attractive source of feedstock for the production of biofuels, algae have emerged as the third generation of biofuels, aiming to reduce land and water requirements (Saad et al., 2019). This section discusses issues related to the characteristics; land utilization; technology; economics; genetic engineering; and challenges of algal biofuels.

Algae have high lipid and carbohydrate content; are simple to grow; grow rapidly; yield a lot of biomass; and produce nontoxic and biodegradable biofuels (Saad et al., 2019). Compared to the first and the second generation of biofuels, algae have high productivity rates; do not depend on fertile soils; and may use salt or brackish water for their cultivation (Correa et al., 2021). Third-generation algae-based biofuels do not pressure agricultural resource allocation and do not threaten food production (Doshi et al., 2016). Efroymson et al. (2017) presented the following comprehensive list of positive and negative characteristics of algal biofuels:

- existence of a wide range of species and strains options
- potential use of genetically modified algae, i.e. using fourth-generation biofuels (which may create issues of social acceptance, making polling public opinion recommended especially in view of perceptions of risks of catastrophic events)
- probable use of nonagricultural land (which implies that they do not necessarily affect food security)
- expensive infrastructure (which affects profitability negatively)
- high energy inputs (which increases energy consumption and affects profitability negatively)
- need for carbon dioxide supplementation (which affects profitability negatively, although carbon dioxide output streams from other industries may be used)
- wide range of potential coproducts (which affects their profitability positively)
- early stage of commercialization (which affects their profitability positively)
- potential occupational hazards from toxins or other water contaminants (which may translate to workdays lost to injury and affect social acceptance negatively)
- and potential susceptibility to hurricanes and other natural disasters (with related risks of catastrophic events affecting social acceptance).

Gomiero (2015) added the following drawbacks:

- algae share one another resulting in different light saturation levels in the cultures
- algae growing in open ponds can be affected by predators, disease and contamination
- efficiency is limited by the fact that the produced algal oil is the algae's natural defense against long periods of limited sunlight and nutrients.

Indeed, one of the most significant advantages of third-generation biofuels is that the cultivation of algae does not require arable land, so it does not trigger land use competition with food crops or deforestation (Rösch and Maga, 2012). In fact, the land footprint required by first-generation (maize, sugarcane, and oil palm) or second-generation (switchgrass) biofuel production systems would be at least three times greater than that required by algal biofuel production systems (Correa et al., 2021).

2.3.1. Production of algal biofuels

Many algal species may be used to produce biofuels, including chlorophytes (macro and microalgae) (Saad et al., 2019). Wastewater carries algae resulting in the development of mixed cultures containing different algal species (Rösch and Maga, 2012). Marine microalgae have also been identified as a possible feedstock for third-generation biofuels (Doshi et al., 2016). The sugars present in marine microalgae are suitable for bioethanol production, while the higher growth and lipid accumulation capacities of microalgae is good for production of biodiesel.

A temperature between 20 and 30°C is considered suitable for most algal species (Saad et al., 2019). The feedstock production chain of algal biofuels resembles that of conventional biofuels, including: feedstock production; feedstock logistics; conversion to biofuel; biofuel logistics; and biofuel end uses (Efroymson et al., 2017). Phases in biodiesel production from algae include cultivation, harvesting, lipid extraction, and conversion to biodiesel (Doshi et al., 2016).

The cultivation of algae is an important step in the production of biofuels and may be done in photoautotrophic or heterotrophic algal systems (Saad et al., 2019). Photoautotrophic systems use light while in heterotrophic systems, algae need organic carbon to feed in the dark (possibly competing with other biofuels technologies for feedstock). Photoautotrophic systems include open pond and closed reactor systems. Mixotrophic systems, in which cells can grow autotrophically or heterotrophically based on the available energy source, are reported to be the best way to maximize biomass and lipid productivity.

Algae is cultivated in controlled artificial aquatic environments with growth media rich in nutrients and carbon dioxide (Doshi et al., 2016). These include both open ponds (shaped like raceways) and closed photobioreactors (PBRs). Compared to closed systems, open pond systems are less expensive, but less controlled (Saad et al., 2019). Open pond systems can use the atmospheric carbon dioxide, so their location is associated with sunlight availability. Closed reactor systems (photobioreactors) are more expensive, but have higher productivity rates than open ponds due to the controlled growth conditions. Hybrid systems combine open and closed systems and are designed to overcome the big initial and operating costs of closed systems as well as the limitations of open systems. Hybrid systems can achieve excellent biomass productivity and high nutrient removal.

Harvesting is the process of collecting algal cells from their medium without affecting their water content (Saad et al., 2019). This is oftentimes done by combining different harvesting methods. The cultivated algal biomass is processed (like other lipid-based feedstock) to produce biodiesel, while the carbohydrates in the algal cells may be fermented to produce bioethanol. The process of breaking down biomass into fuel or nonfuel products with environmentally friendly methods is called biorefining. Biorefineries can increase the cost effectiveness of producing biofuel from algae through the development of valuable coproducts such as protein (Correa et al., 2021).

Increasing the yield of algal biofuel production is a key factor to reducing their cost (Villarreal et al., 2020). To that end, genetic engineering can help increase algal productivity and yield and make fuel harvesting more efficient. Such genetic manipulation of algae helps with their commercialization, so the use of genetically modified organisms in algal biofuel production is expected to grow (Efroymson et al., 2017).

2.3.2. Economics and challenges of algal biofuels

On the economics of algal biofuels, it is considered that they still cannot compete with fossil fuels (Villarreal et al., 2020). Furthermore, there is criticism of the financial viability of cultivation and conversion technologies of marine microalgae (Doshi et al., 2016). It is argued that the production of biofuels from algae is economically unsustainable and can help in the fight against climate change only under specific conditions (Villarreal et al., 2020). Comparing the production of conventional to that of algal biofuels is not trivial. An important difference is that most start-up algal biofuel companies are engaged in the entire supply chain rather than being focused on one step, as is the case with most companies in the conventional biofuel industry (Efroymson et al., 2017).

Presently, the industry of algal biofuels is at a relatively early stage (and scale) of commercial development (Efroymson et al., 2017). The key challenges appear to be the high infrastructure, operation, and maintenance costs (especially compared to terrestrial biofuels); the (need for) selection of appropriate high lipid containing algal strains; the requirement for supplemental carbon dioxide; efficient harvesting at a commercial scale; and addressing important issues like water evaporation (Saad et al., 2019; Efroymson et al., 2017). Technological improvements are expected to lower the production cost of biofuels; decrease their nutrient usage; and optimize their carbon and energy balances (Correa et al., 2021). Threats to the continuous supply of algal biofuels must also be addressed, like pathogens and predators that cause algal pond crashes or extreme weather events that impact cultivation (Efroymson et al., 2017). Like any new technology, biofuels are likely to start with a number of competitive disadvantages including the requirement for new infrastructure, new processing facilities, and new logistical challenges (Wegener and Kelly, 2008).

3. Socioeconomic aspects of biofuels

(Algal) biofuels have several socioeconomic aspects, which produce positive (favorable) and negative (unfavorable) impacts (Sawyer, 2008) affecting social well-being. This section discusses the social aspects of biofuels related to sustainability; land requirements; employment and income; food security; costs and prices; and gender and culture.

Social well-being refers to basic human needs such as food, health, and shelter (Efroymson et al., 2017) and may be measured by socioeconomic indicators such as the following (Efroymson et al., 2017; Xi and Long, 2016):

- Income and employment, which are affected to the extent that biofuels provide well-paying jobs.
- Household income, which is affected when biofuels provide well-paying jobs and decrease fuel costs.
- Workdays lost to injury, which may be avoided by selecting algal strains and conversion processes that minimize exposure to toxins.
- Food security, which is impacted favorably by algal biofuel systems that are developed on nonagricultural lands.

The socioeconomic impacts of biofuels are characterized by uncertainties and controversies (Xi and Long, 2016) some of which remain unresolved, e.g. the magnitude of negative impacts on the supply and prices of food or the induced loss of ecosystem services caused by the clearing of forest land and conversion to feedstock production (Doshi et al., 2016). The third generation of biofuels in particular are reportedly characterized by a number of socioeconomic benefits which contribute to an outcome that is socially sustainable avoiding the negative externalities associated with conventional biofuels. Their potential effects may vary by feedstock, market structure, and local conditions such as geography, social structure, etc. (Elder et al., 2018). Technical progress is considered a major driving force in understanding the impacts of biofuels (Sawyer, 2008).

Large-scale algal biofuel production systems may result in water pollution that might affect people, farm animals, and local wildlife; safety concerns, if the algae are genetically modified; and spread of disease (Saad et al., 2019). Important decisions related to algal biofuel production systems are taken during siting, operations, use of resources, and fuel use (Efroymson et al., 2017). Such decisions interact with stakeholder groups including local residents, industry leaders, and citizens. The installation of various technologies may catalyze social improvements, e.g. the use of saline water for cultivation of algae may allow the production of biofuels in regions that are characterized by freshwater scarcity, e.g. Australia, northwestern Africa, the Arabian Gulf, and deserts in the US (Efroymson et al., 2017).

3.1. Social sustainability

Are algal biofuels associated with social sustainability, i.e. the capacity of current and future societies to satisfy human needs in the context of healthy and livable communities in harmony with the natural environment? Social sustainability presupposes an equitable distribution of economic benefits across urban and regional social communities and their quality of life (Doshi et al., 2016). Its focus has been on consumption, income, employment, democracy, participation, and gender equity (Rösch and Maga, 2012), with a tradeoff among social, environmental, and economic indicators. An important sustainability concern is that the production of conventional biofuels increases the competition between feedstocks and food production for land, water, and labor (Xi and Long, 2016).

Short-term social sustainability for small-scale algal biofuel production processes could be measured by indicators such as workdays lost to injury (Efroymson et al., 2017). Other indicators of social sustainability for biofuel pilot plants could include employment; worker income; workdays lost to sickness or injury; public opinion; effective stakeholder participation; and transparency. Selected indicators of social sustainability for collection of plants (i.e. industry) that produce algal biofuels (large scale): food security; employment; fuel price volatility; depletion of nonrenewable energy resources; effective stakeholder participation; transparency; public opinion; workdays lost to sickness or injury; and household income.

3.2. Land and socioeconomic aspects

Land requirements constitute a big problem for conventional biofuels. Arable land is an increasingly scarce resource (Rösch and Maga, 2012). There is also concentration of land because monocultures of cane and soybeans require large areas for mechanization (Sawyer, 2008). This translates to concentration of income because producers and processors make large profits, while workers are earning low wages or entirely displaced. There are also various side issues. For example, biofuels are behind the explosion of large-scale leases or purchases of African and South American agricultural lands on terms unfavorable to current owners and users (Gonzalez, 2018).

Africa is the epicenter of land grabbing (Gonzalez, 2018). Motivated by the global demand for biofuels, many land grabs are orchestrated by transnational corporations. Small farmers and herders may be evicted or forcibly relocated by government elites, foreign investors, or even local elites seeking to lease or sell their land to foreign investors. In addition, some biofuel companies may displace people from land without sufficient compensation (Xi and Long, 2016). As a result, there are several negative impacts of large-scale land deals, including: threatening the livelihoods of small farmers by evicting them from lands traditionally used for food cultivation; depleting or contaminating the local water supply; and depriving locals of the access to grazing lands, forests, adjoining fisheries, and other natural resources essential for their survival (Gonzalez, 2018).

3.3. Employment and income

Turning to employment and income, the welfare effects of conventional biofuels are complicated (Doshi et al., 2016). The development of conventional biofuels takes place in rural areas, with much of it done by small scale and subsistence farmers in developing countries. The potential for employment and income generated by the production of biofuels from crops and improvements in fuel access, may offset higher food prices especially in poor regions. Not to mention that higher food prices provide additional income to farmers. New companies garner political, economic, and social support in a region by projecting the number of jobs that will be created (Efroymson et al., 2017). Sawyer (2008) has asserted that soybeans *“eliminate employment”* and sugar cane results in *“temporary semi-proletarianization”* in unhealthy, exhausting conditions. Neither benefits nor damages are shared equally across society.

Xi and Long (2016) have suggested that the development of biofuels improves the income of farmers in the short term, providing them with employment opportunities and mobilizing them to grow food (although these positive effects may be limited and unstable). To be more specific, the cultivation and processing of biomass feedstocks to produce biofuels and their subsequent conversion to heat and power, transport fuels, and byproducts, creates new opportunities for many categories of workers including farmers; forestry workers; engineers; construction workers; biofuel companies; research institutions; and workers in support industries (“Societal Benefits of Biofuels in Europe”, n.d.). Interestingly, it has been suggested that such increases in employment and income may have shifted concerns away from potential siting controversies for new plants (Chin et al., 2014).

There may be difficult tradeoffs between economic costs and desired socioeconomic impacts (Elder et al., 2018). For example, maximizing employment and income for farmers and workers may require labor intensive, smaller-scale production methods which entail higher wages. On the other hand, biofuel producers prefer large-scale mechanized production that minimizes costs and maximizes profits through labor saving. Unfortunately, such large-scale production is more likely to result in widespread deforestation with significant negative impacts on ecosystems.

Some researchers have suggested that the production of biofuels increases the competition between feedstocks and food production for land, water, and labor, which results in lower income, higher food prices, and lower purchasing power of households (Xi and Long, 2016). In any case, because of the fragility and complexity of the energy market, the impact of the biofuel industry on the employment and income of farmers is considered to be unstable.

Compared to conventional biofuels, algal biofuels are likely to create jobs by attracting capital investment and innovative technologies. They are also likely to generate indirect employment for suppliers of resources and technologies necessary for algal biofuels (e.g. nutrients, carbon dioxide, liners, pumps) as well as industries that provide resources to biofuel facilities (Efroymson et al., 2017). Since algal biofuel plants are designed for decentralized production based on local nutrient streams, algae can support local employment (Rösch and Maga, 2012). This agrees with the recommendation by the United Nations Conference on Trade and Development for a move away from industrial agriculture and towards small-scale production that is likely to be more sustainable (UNCTAD, 2018). Unfortunately, it has been argued that given the high cost of infrastructure and the industrial expertise required to cultivate algal biofuels, employment and income indicators are unlikely to be incentives for small landholders who will prefer terrestrial feedstocks (Efroymson et al., 2017).

Net job creation is considered the principal economic benefit of biofuels (Efroymson et al., 2017). For conventional as well as algal biofuels, job opportunities in the bioeconomy are likely to translate higher rural wages and progress towards sustainability. Contrary to fossil fuels that depend on finite resources and conventional biofuels that are restricted by objective resource limitations, algal biofuels are a truly renewable energy industry that can sustain long term fuel demands, generate employment (across skill levels) and income, and provide opportunities for economic growth in regional and regional communities, many of which typically depend on seasonal industries (Doshi et al., 2016).

Stakeholders are those involved in and affected by the interaction of biofuels with employment and income, including social actors that are exposed to the impacts of biofuels related to employment and income and likely have special interests in the development of biofuels. These actors include facilities, industries, municipalities, and states with goals for employment and income (Efroymson et al., 2017) with reference to energy security, resource conservation, and employment. Biofuel industries provide opportunities for economic growth in non-metropolitan and regional areas with private and public investments to be centered on employment and income opportunities for local agricultural industries, business and communities (Doshi et al., 2016). What distinguishes algal from conventional biofuel industries is that many of the business models used in algae are based on innovative high-level technologies, thus providing employment for scientists, engineers, and technicians in research, manufacturing, operation, marketing, and monitoring (Rösch and Maga, 2012).

3.4. Food security and society

Employment and food security are important issues for (algal) biofuels (Efroymson et al., 2017). Any negative impacts of conventional biofuels on food accessibility are realized by eliminating or degrading local jobs, decreasing the income of households while at the same time increasing food prices, ultimately lowering the purchasing power of households (Xi and Long, 2016). Areas most vulnerable to food security are impoverished regions especially in developing countries where agriculture is the pillar industry. One interesting suggestion is the reuse of abandoned crops for the production of biofuels, which conforms to the model of a recycling economy, saving resources and improving the efficiency of their use (Xi and Long, 2016).

In any case, algal biofuels are likely to have positive impacts on the access to food, adding employment opportunities, stimulating rural economies, and decreasing vulnerability to shocks in the price of food.

3.5. Costs and prices

The development of biofuels is connected to economic growth (Xi and Long, 2016). The wider economic importance of algae may be appreciated considering their uses in wastewater treatment, energy cogeneration, bioremediation, fertilizers, animal fodders, and medicinal compounds and health products (Saad et al., 2019). The development of algal biofuels could stimulate economic growth and alleviate poverty in developing countries that are likely to be heavily involved in their production (Xi and Long, 2016).

Algal biofuels are considered an expensive source of renewable energy that are capital and resource intensive (Doshi et al., 2016). Aside from the construction and maintenance of the artificial environments necessary for their cultivation, algae have substantial energy, water, and nutrient (such as nitrogen and phosphorus), and carbon dioxide (which may be obtained from the output feeds of other industries) requirements. Although some waste resources may be recycled, their high energy requirements suggest a dependence on fossil fuels at least in the short to medium term. On the other hand, algae are cultivated in artificial environments, so they do not demand arable land (Doshi et al., 2016) nor they compete for water resources (Saad et al., 2019). With their expansion as feedstock, the cultivation of algal biofuels will shift away from agricultural land and both macro and microalgae will help reduce the opportunity costs associated with scarce land resources being used for the cultivation of energy rather than food crops.

The economic costs of biofuels depend on technology and feedstock (Xi and Long, 2016). Compared to the production of conventional biofuels that are based on agriculture, the production of algal biofuels is characterized by higher startup costs (Doshi et al., 2016) and very high infrastructure investment especially for large scale facilities (Saad et al., 2019). The energy cost of algal extraction is ten times that of soybean oil extraction. Prospecting for different macro and microalgae to produce affordable biofuels entails identifying high-lipid species from various habitats. As technology evolves and their production costs are reduced, algal biofuels could complement and possibly replace conventional biofuels (Correa et al., 2021).

Currently, algal biofuels are barely able to compete with fossil fuels in terms of price (Doshi et al., 2016). This may change as related technologies improve and mature. In any case, the economic benefits of biofuels depend on external factors such as fluctuations in energy markets, extreme weather events, and subsidy policies (Xi and Long, 2016). The cultivation of algae integrated with existing complementary industries is a good strategy (Doshi et al., 2016). The income of seasonal industries may be supplemented, while the synergy from the biofixation of waste effluents and production of usable coproducts (such as feed and fertilizers) could be beneficial to local communities.

Justifying support for conventional biofuels is made difficult by their negative societal impacts related to food prices and resource constraints (Doshi et al., 2016). Conventional biofuels compete with food production and impact the allocation of agricultural resources and food prices, competing land and capital with grain and beef (Sawyer, 2008). As pressure is put on farmers to convert food crops, first-generation feedstock has been found to have a bigger effect on food than energy prices.

The production of biofuels has direct (e.g. on the price of corn) and indirect (by decreasing acreage available for food crops, reducing food supply) impacts on the prices of agricultural products (Xi and Long, 2016). For example, the growth of demand for bioethanol leads to an increase in the prices of related agricultural products with a corresponding increase of the income of farmers in developing countries. Oftentimes, foreign investors are entitled to financial compensation, as when the state allocates water rights to local residents or restricts the export of agricultural products to prevent domestic food shortages (Gonzalez, 2018).

Algal biofuels produced domestically can create economic opportunities for local communities as well as help attenuate uncertainties associated with global energy markets (Correa et al., 2021). Price is a major concern when purchasing fuel in global energy markets (Chin et al., 2014). In general, the price of biofuels is higher than that of fossil fuels. When the two becomes equal, other considerations enter the picture, such as refueling convenience; (perceived) safety to users and the public; fuel performance; ownership cost; reduced social impacts, such as lower food prices; and environmental impacts including carbon emissions (Chin et al., 2014).

The biofuel boom of the 2000s was in fact supported by high oil prices while the subsequent fall of oil prices harmed the economic viability of biofuels (Elder et al., 2018). There are also positive rebound effects in action, e.g. an increase in biofuel consumption may lower the price of oil, leading to higher oil consumption (Xi and Long, 2016).

3.6. Gender and culture

The socioeconomic aspects of algal biofuels also relate to culture and gender inclusion. The displacement and seasonal labor that is associated with conventional biofuels exert pressure and degrade family farms and traditional communities (Sawyer, 2008). The expansion of algal biofuels with a corresponding reduction of conventional biofuels should reduce the workload of women and children in the Global South who are oftentimes in charge of collecting firewood.

Culturally, large-scale algal oil production may involve delays in accepting new and unconventional practices (Saad et al., 2019). Algae are unlikely to harm cultural heritage, e.g. by damaging buildings and monuments by acidification (Rösch and Maga, 2012). Similarly, cultural and natural landscapes of particular beauty are unlikely to be damaged by nearby algal biofuel production plants (Rösch and Maga, 2012).

3.7. Public acceptance

Public acceptance is an important social aspect of biofuels. This section discusses the following issues in reference to the public acceptance of (algal) biofuels: stakeholders; influences and factors; public attitudes; social norms; acceptance; expert opinions; biofuel specifics; indicators; and empirical research.

The stakeholders whose opinion is of interest as regards the social acceptance of biofuels include citizens; businessmen; social and ecological organizations; public authorities; and politicians (Rösch and Maga, 2012). Local stakeholders include farmers, residents and local authorities (Chin et al., 2014). Different social groups consider different biofuels dimensions along the production life cycle (Chin et al., 2014). For example, for conventional biofuels, local farmers may resist crops and practices they are unfamiliar with (Chin et al., 2014).

3.7.1. Influences and factors

Turning to perceptions, the behavior of people in social settings is influenced by individual, social, political, and societal factors (Wegener and Kelly, 2008). Social psychology aims to understand the influence of social factors on perceptions and behavior. Participating in decision making is important for social agents (Rösch and Maga, 2012).

The media has played an important role in shaping public perceptions about the benefits and drawbacks of biofuels (Chin et al., 2014). Cacciatore et al. (2012) found that the wording used may affect public perceptions, e.g. the word *"biofuel"* is perceived as more environmentally friendly than the word *"ethanol"*, which is linked to the food versus fuel debates.

3.7.2. Public attitudes

As discussed by Paravantis (2010), the theories of reasoned action (Ajzen and Fishbein, 1980) and planned behavior (Ajzen, 1985) imply that explicit behavior is preceded by behavioral intention. Also, apparent beliefs are necessary conditions for any attitude (Stutzman and Green, 1982) which may be complex entities with components of behavior that are beyond volitional control (Kaiser et al., 1999). Attitudes are of interest because they can influence behaviors (Wegener and Kelly, 2008). In fact, attitudes have been found to predict behavior when the influence of other psychological constructs such as values and subjective norms are controlled.

Trying to understand and predict individual behavior, psychologists, consumer scientists, and behavioral economists have focused on specific attitudes, beliefs, and decision processes that are believed to influence behavior (Wegener and Kelly, 2008). Factors that contribute to weak attitudes about a subject include insufficient knowledge; lack of direct experience; inaccessible memories; and little previous thought.

Furthermore, people tend to pay attention to messages that agree with the position they already hold (Wegener and Kelly, 2008) – this is called confirmation bias or cognitive dissonance. On the other hand, people tend to think carefully about topics they are ambivalent about. In fact, people feel uncomfortable when they are ambivalent, so they are motivated to seek information that helps reduce their ambivalence. Such information may not be objective, as it is filtered through confirmation bias. In the case of biofuels, ambivalence may occur, e.g. when people believe that ethanol is good because it supports farmers or uses carbon dioxide to grow the feedstock (thus helping address climate change), but at the same time they think that ethanol is bad because it is grown on agricultural land that is normally used for food crops or because they have heard of negative impacts of agricultural runoff on the hydrosphere (streams and rivers).

In some settings, behaviors are predicted by how people perceive the opinions of other important or famous people (Wegener and Kelly, 2008). Exposure is also good, so increases in biofuel-related communications (e.g. television ads) are likely to increase the accessibility of attitudes towards biofuels, making them more likely to predict actual behavior. Yet, favorable attitudes alone are not enough to have a lasting impact on thinking and behavior – they must also be strong. Favorable attitudes towards biofuels may not be strong enough to result in their approval or even actual consumption.

In the case of biofuels, public opinion is likely to be (positively or negatively) affected by the potential for new employment opportunities; aesthetics; odors; (recent) media reports about algae; perceptions of genetically modified organisms (if used); perceptions of renewable fuels; and perceptions regarding sustainability (Efroymson et al., 2017). When addressing a group of people who are ambivalent about biofuels, it is important to couch one's message in a way that the audience would agree with it (Wegener and Kelly, 2008). For example, when addressing people concerned about the environmental impacts of biofuels, it is advisable to begin one's message by emphasizing the environmental problems that can be addressed by moving from fossil fuels to renewable and environmentally friendly energy sources.

It should be kept in mind that consumers are not limited to end users but also include investors and producers (including prosumers) (Chin et al., 2014). In an area where the production of electricity from small-scale renewable energy installations is already widespread, it is more likely that people would be open to other small-scale energy projects including algal biofuels.

3.7.3. Social norms

Although people like to think of themselves as independent and sophisticated, their need to belong and their belief that consensus implies correctness constitute strong influences on thinking and behavior adoption (Wegener and Kelly, 2008). In addition to personal attitudes, the wider social context can also exert a powerful influence on the behavior of people. While attitudes reflect individual evaluations, norms reflect the evaluation of a wider social group.

Norms can influence behaviors beyond the attitudes that people hold (Wegener and Kelly, 2008). For one, the behavior of people may change due to their wish to conform to the norms of the social group to which they (consider that they) belong. Also, people may adhere to the standard of a group they wish to enter or because they want to stand up to the expectations of others. Finally, people may behave so because they do not want to alienate people from their own social group.

To predict people's attitudes towards biofuels, one would like to know the attitudes of the people towards related technologies as well as any relevant social norms instituted locally (Wegener and Kelly, 2008). Social norms are important for the acceptance and adoption of biofuels. As an example, an initial diffusion of flexible fuel vehicles into the market may help build a social norm and thus increase and establish their presence. As another example, if some of your neighbors purchased vehicles that run on ethanol-based fuels, a local norm might develop that conveys the notion that purchases of such vehicles are accepted and supported by society. Eventually, you may be inclined to buy a flex fuel vehicle yourself.

Not everyone behaves the same way though. Subjective attitudes and social norms may be more important for some people rather than others (Wegener and Kelly, 2008). As an example, older people have experienced more political and international conflict than younger ones, so they tend to worry more about it (Zavvanidou et al., 2009). Therefore, presenting algae to them as a means of biofuel production that does not affect agriculture; helps avoid land conflict; does not affect food prices and security; and helps with energy security, would be more appealing to older people.

On the other hand, older people may be more concerned about energy dependence locally because they tend to focus on family, friends, etc. (Zavvanidou et al., 2009). This finding agrees with Dourmas et al. (2019) who carried out an online survey of attitudes towards environmental and energy problems, impacts, and policies. They established the existence of three clusters among Greek respondents: the oldest respondents were people with families, who were less concerned about contributing to climate change, and more concerned with regional and local effects including the impacts of climate change on small business development, economic middlemen, economic concentration, and local production.

The power of group norms is such that they can influence judgments and behaviors even when objective, unambiguous information is available (Wegener and Kelly, 2008). Information, individual perceptions and social norms interact: when people were given accurate information about the energy consumption of themselves and their neighbors, those who used more energy than their neighbors decreased their energy consumption. On the other hand, people often rely on heuristic shortcuts to make sense of complicated and controversial situations (Villarreal et al., 2020). When information is lacking, people consider group norms to be representations of reality, and base their perceptions and judgment on them (Wegener and Kelly, 2008). Here is an unexpected finding: telling people how widespread the energy overconsumption problem is, may convey to them the notion that many people choose to consume a lot of energy, which makes it a social norm that can have the opposite of the intended effect, i.e. making people consume more (rather than less) energy. Information about local norms may even come from the environment, e.g. if an area is messy or not clean, people are more likely to litter there.

The importance of social norms explains why the opinion of experts is consequential: when it comes to the adoption of new technologies such as purchasing ethanol or a flexible fuel car, people look to the norms of important reference groups to help them decide (Wegener and Kelly, 2008). At the same time, people who belong to a different generation, or live in a very different social environment, or are of a different ethnic background, etc. may be viewed as too dissimilar to matter.

An effective public campaign should urge people to adopt an environmentally friendly behavior not because they might save money nor because they should be socially responsible, but because most of their neighbors do so as well (Wegener and Kelly, 2008). Objective information is also important, for example positive attitudes towards the use of biofuel are more likely to guide future fuel choices if they are based on the actual driving of a car using an ethanol-based fuel rather than mere information on ethanol-based cars. All in all, it is important to create attitudes and norms favorable to the use of algal biofuels that are unambiguous and strong enough to bring about the desired behaviors.

3.7.4. Social acceptance

Turning attention from social norms to acceptance, addressing social concerns may help a technology be accepted by the public (Wegener and Kelly, 2008). The research literature includes studies of both social acceptability and social acceptance: acceptability refers to the judgment of a technology before it has been used, while acceptance refers to the judgement as well as behavioral reactions towards a technology after it has been used (Martin et al., 2016). This distinction is not very relevant in the context of algal biofuels because they are a new technology to which the public largely has not been exposed to.

It has been suggested that social acceptance contains (and must be explained within the context of) three dimensions: sociopolitical, community, and market acceptance (Wüstenhagen et al., 2007). It has also been argued that only when considering all these three dimensions may a complete picture of social acceptance be obtained (Chin et al., 2014).

Social acceptability may be measured by: (favorable) public opinion; transparency (e.g. timely reporting of relevant performance data); (effective) stakeholder participation; and risk of catastrophe (of similar technologies) (Efroymson et al., 2017). Safety of operations, workdays lost to injury, and trust are also important for social acceptability. Costs and benefits influence acceptability, but their association is in part determined by psychological factors. Perceptions may be affected by media coverage while social acceptability may be affected even by claims that are unsupported by science. Social acceptability is also sensitive to location: some technologies may be accepted in some locations, but rejected in others. Social acceptability may change over time and social acceptance is a dynamic process, involving the interaction of different stakeholders (Chin et al., 2014).

Public acceptance refers to the most general form of acceptance which concerns the entire society regardless of specific societal groups (Chin et al., 2014). Sociopolitical acceptance refers not only to the general public, but to stakeholders and policy makers as well. Stakeholder acceptance is different from that of the general public. Effective stakeholder participation helps not only transparency, but public acceptance as well (Efroymson et al., 2017).

Community acceptance deals with controversies at the local level and has received much attention in the research literature (Chin et al., 2014). Residents and local authorities are the main local stakeholders and the core interest of the community dimension of social acceptance is spatial planning. The main factors for community acceptance are procedural justice, distributional justice, and community trust.

As a new generation of renewable energy sources (such as algal biofuels) arrives, customer acceptance may determine the extent to which policy makers and the industry support their widespread development and diffusion (Wegener and Kelly, 2008). While studies have established a societal preference of renewable energy, a NIMBY (Not in My Back Yard) attitude has been established in several studies (Zavvanidou et al., 2009) referring to public opposition usually during the beginning of the construction phase of renewable energy facilities (Chin et al., 2014). Some scholars claim that acceptance reflects support while willingness to use or purchase is a form of self-reported behavior. Willingness to use or purchase may be viewed as active social acceptance. Other scholars consider social acceptance to be passive consent (rather than public voluntary support). In any case, public participation, (perceived) fairness, and influence from the media play a role in NIMBY phenomena.

Social acceptance may also be viewed as passive when it is motivated by government policies (Chin et al., 2014). The presence of both active and passive social acceptance flags the acceptance of innovative technologies. Market acceptance concerns the diffusion of renewable energy technologies into the market. In the case of biofuels, market acceptance would mean that consumers prefer choosing biofuels for their vehicles. Rösch and Maga suggested that an acceptance analysis would help identify possible barriers to acceptance; this information could be used to select optimal locations for algal biofuel production plants (2012).

It has been suggested that public acceptance for algal biofuel scenarios should be above 50% (Efroymson et al., 2017). It has been argued that it is citizens that are concerned about security, environmental preservation, and local economic development that are willing to pay a premium for the development of new energy sources like biofuels (Wegener and Kelly, 2008). On the other hand, local residents may be concerned with water competition between domestic usage and biofuel production (Chin et al., 2014). Intra-firm acceptance is another dimension of concern in this respect, related to the adoption of renewable energy by the business sector.

Even if local residents welcome biofuel plants, future changes in their technology and infrastructure may create confrontation (Chin et al., 2014). Also, the factors that are crucial for acceptance in one sector of renewable energy, e.g. wind, may not identical to those that are important in the case of biofuels. Furthermore, trust is especially important for the social acceptability of technologies involving genetic engineering (Efroymson et al., 2017).

All in all, the existence of relatively few studies and the high dispersion of their results show that more work is necessary to clarify the social acceptance of biofuels (Zavvanidou et al., 2009).

3.7.5. Role of experts

Reference groups are viewed as important when they are considered good sources of information and people are likely to identify with them or admire them. A group of experts may play the role of such a group (Wegener and Kelly, 2008). As mentioned in the section on social norms, people are likely to interpret expert opinions positively even if they contain ambiguities. The responses of academic experts are likely different from those of the general public (Villarreal et al., 2020). Nevertheless, an expert source may also serve the role of a strong peripheral cue when people are not able or motivated to think about a message, leading to a conclusion that the expert is correct (Wegener and Kelly, 2008).

Transparency is important for social acceptability, and when lacking in scientists and engineers, it is likely to correspond to transparency lacking in stakeholders (Efroymson et al., 2017). Involving scientists that have minimal conflicts of interest, holding independent peer review, and allowing the public to participate are important (Villarreal et al., 2020). In the case of people who are perceived as outsiders, their trustworthiness must be enhanced (Chin et al., 2014). Showing benefits clearly, communicating risks and benefits unambiguously, and using closed production systems with high security standards can help improve the social acceptability of genetically modified algal biofuel production systems.

3.7.6. Perceptions of biofuels

Energy-related behaviors (including the use of new energy products) and support for policy makers who endorse particular energy policies are influenced by economics; policy alternatives; public/political technology acceptance; and energy-related decision making (Wegener and Kelly, 2008). These are integrated in various theories that help understand the public acceptance of renewable energy without labeling opposition as deviant behavior (Chin et al., 2014).

Biofuels are largely out of sight and out of mind. Biofuels have not taken a central place in public consciousness, so attitudes towards biofuels lack the strength that would enable them to guide public behavior (Wegener and Kelly, 2008). Of the renewable energy sources, wind power has received the most attention in the study of social acceptance (Chin et al., 2014). The promise of bioenergy to supply a substantial portion of transportation fuels hinges on the acceptance of biofuels by both producers and consumers (Wegener and Kelly, 2008).

In the context of biofuels, social acceptance has been considered a requirement for social sustainability (Chin et al., 2014). The lack of social acceptance can hinder the development of alternative energy sources like biofuels. The problem is that only few people think spontaneously about biofuels (Wegener and Kelly, 2008). Furthermore, attitudes towards biofuels are not based on high levels of knowledge – this is bound to be more so in the case of algal biofuels. In fact, people may be more favorably inclined towards bioenergy produced from organic household wastes or manure than crops or even algae.

The transition to biofuels will depend on a combination of social, economic, and political factors. Uninformed citizens are likely to continue favoring familiar energy sources. Suppliers of fossil fuels may attempt to forestall or at least slow down the widespread adoption of alternative energy sources (Wegener and Kelly, 2008). If there are enough people that support the development of biofuels, strong favorable norms may be developed.

A main reason for the resistance of local communities towards the placement of renewable energy projects may be the lack of public involvement (Chin et al., 2014). It has been suggested that local residents who perceive that they have been treated fairly are likely to have a favorable perception of renewable energy projects. Residents may disapprove new technologies because they feel uncertain about their impacts. Similarly, changes in current technology may trigger reaction among local residents.

The lack of market penetration of biofuels may be partially caused by overlooking their social acceptance (Chin et al., 2014). Although it is often ignored, public opinion may be important for the fate of a facility (Efroymson et al., 2017). It is also important (for their eventual acceptability) that biofuels achieve better engine performance (Villarreal et al., 2020).

There are opportunities and strengths regarding the future adoption and diffusion of biofuels for transportation (Wegener and Kelly, 2008). Decentralized production will increase the number of biofuel installations and make them more visible, so their interaction with societal groups will increase (Chin et al., 2014). Examination of the factors that influence consumer behavior may help determine which public perceptions create obstacles to the adoption of biofuels, as well as how such obstacles may be overcome (Wegener and Kelly, 2008). Weak attitudes and few opportunities to support biofuels publicly (e.g. due to few filling stations selling biofuels) may not be enough to create a snowballing effect that will build a favorable consensus in public behavior.

The issue of acceptance of algal biofuels by the markets remains an open question (Villarreal et al., 2020). Social and contextual factors play a crucial role in managing the transition from fossil fuels to renewable energy especially algal biofuels, which by their nature favor the development of only weak attitudes towards them (Wegener and Kelly, 2008).

While algal biofuels appear to be positively viewed by the public regarding their sustainability, other biofuel feedstock (like *Eucalyptus*) are negatively viewed due to their invasiveness and high water demand (Efroymson et al., 2017). Support for biofuel policies is also affected by their interaction with food prices, deforestation, and climate change risks. Food and deforestation considerations are clearly less of an issue with algal biofuels while their contribution to economic development may help gain community support.

The social acceptance of algal biofuel production systems is likely to be high if their advantages over conventional biofuels are demonstrated, stressing their environmental benefits such as wastewater remediation and carbon dioxide capturing (Rösch and Maga, 2012). No information is available on the willingness of people to promote (and pay for) algal biofuels or their environmental and social benefits. Strengthening positive attitudes is easier than converting negative to positive, so it would be helpful if people did not harbor negative attitudes towards algal biofuels (Wegener and Kelly, 2008).

Finally, regarding gene modifications (in fourth-generation biofuels), environmental groups might be concerned about genetically modified species spreading genes to the local environment (Wegener and Kelly, 2008). Public opposition to genetically modified organisms may differ among countries (Efroymson et al., 2017), but transgenic algae are not food from transgenic plants that people would probably not want to consume (Wegener and Kelly, 2008).

3.7.7. Biofuel indicators

Various indicators related to biofuels have been used in related research. These represent social well-being; energy security; profitability; external trade; resource conservation; and social acceptability (Efroymson et al., 2017). Socioeconomic indicators are perceived as having different importance for different sectors: profitability is important for the industry; employment is important for the general public; and social acceptability is important for Nongovernmental Organizations (NGOs).

The following characteristics and corresponding indicators of algal biofuel production may affect public opinion (Efroymson et al., 2017):

- probable use of nonagricultural land, which may affect food security positively
- large volumes of freshwater demanded by some cultivation system, which may affect water quantity negatively
- possible use of wastewater, which may affect water quality and profitability positively.
- possible odors from cultivation systems, which may affect air quality negatively
- possible toxins as occupational hazards, which may affect workdays lost to sickness or injury positively
- potential uses of carbon dioxide from utilities or other industries, which may affect profitability positively and greenhouse gas emissions negatively
- blooms, which are a property of some algae, which may affect water quality negatively
- possible breaches caused by natural disasters, which may affect risk of catastrophe positively
- expected use and possible release of genetically modified organisms, which may have both positive and negatively effects on biodiversity
- potential for automated processes, which may affect employment negatively
- renewable fuel development, which may affect energy security positively

- and need for research and development, which may affect employment positively.

3.7.8. Empirical research on public acceptance of biofuels

Attention now shifts to some of the limited empirical research on the public acceptance of biofuels. Chin et al. (2014) argued that there were few studies investigating the public acceptance of biofuels. Initially, those studies focused on the opinion of the general public rather than that of specific societal groups. Chin at al. focused on Malaysia, a developing country, and examined issues related to the social acceptance of biofuels intended for domestic usage. It was argued that public acceptance issues must be confronted at the early stage of biofuel production to ensure the continuous supply of feedstock.

A conceptual framework for the social acceptance of biofuels was presented (Chin et al., 2014). Sociopolitical acceptance was the most general level, forming the outer boundary. The dimensions of community and market acceptance were within the boundary of sociopolitical acceptance, focusing on corresponding issues. Sociopolitical acceptance was considered to refer to the opinion of the general public, stakeholders (including industry players and environmental protection groups), and policy makers in matters related to biofuels.

Community acceptance was considered to refer to the collection and production of biofuels (Chin et al., 2014). The community dimension of acceptance is associated primarily with the siting of biofuel projects with land right conflicts being prominent. Annoyances like haze pollution are also linked to public acceptance and, to be addressed, they would necessitate collecting rather than burning harvesting residuals. The willingness of planters and producers to collect harvesting and production residuals are also related to community acceptance. Adoption of modern cultivation techniques and sustainable farming practices are another challenge for community acceptance. Regarding the fourth generation of biofuels, it was argued that although using genetically modified crops for biofuel generates public acceptance issues, the genetic modification of nonedible crops (as in the case of those intended for biofuel production) is more acceptable.

Efroymson et al. (2017) reported that little has been published on the public opinion about algal biofuels. They argued that most existing studies of stakeholder perceptions of algal biofuels present barriers and opportunities (rather than concerns) about environmental or social impacts. It has been recommended that nonarable lands be used for cultivation; genetically modified organisms be avoided (because of the difficulty of addressing leakage); and more attention be devoted to water requirements.

Efroymson et al. (2017) cited literature evidence that indicated a positive public opinion about algal fuels. They mentioned a study in which sustainability considerations appeared to increase the sales of fuel derived from algae. In another study, 92% of respondents noted that (perceptions of) environmental benefits made them more likely to purchase fuel derived from algae. In another study, 40% of respondents even indicated that they would be willing to pay a premium for fuel derived from algae.

Perception of a fuel as renewable may affect public opinion and determine community support, although biomass may not be recognized as a renewable energy source (Efroymson et al., 2017). People evaluate renewable fuels favorably even when the environmental effects of concern are not clear. Yet, public opinion may vary from one biofuel to another. Place attachment can also affect public opinion, depending on whether a project is considered a local threat or opportunity.

The authors state that public perceptions of algae (in general) in western nations are sometimes negative, conjuring images of green tides or toxic blooms (Efroymson et al., 2017). Although there is a concern about genetically modified organisms (especially in agriculture), concerns about microorganisms relate more to potential environmental impacts rather than health or ethical issues. Public concern about genetic modifications may be increased in the case of outdoor testing and usage. In addition, there may be greater uncertainty regarding the impacts of genetically modified organisms on the environment in the public of developing countries.

Villarreal et al. (2020) presented the results of a survey conducted in the context of a Horizon 2020 project (http://www.photofuel.eu). Respondents regarded fossil fuels as the most risky; and wind power, hydropower, and solar panels as the most harmless energy options. For algal biofuels, the strongest agreement was found in the case of no competition with food production. A weak agreement with superior engine performance was associated with lack of sufficient knowledge. Algal biofuels and hydropower were the two energy sources for which people were less informed. It was also found that the educational level of consumers was associated with a higher willingness to use genetically engineered algal biofuels, although the number of respondents who indicated that they did not know increased with educational level. A clear and strong relationship was that respondents with a higher educational level gave more importance to the clear communication of risks and benefits of genome engineering technologies.

Respondents who worked in education were more likely to agree that one of the benefits of genetically engineered algal biofuels (compared to fossil fuels) is that they do not compete with food production (Villarreal et al., 2020). Respondents working in the industry were more skeptical about genetically engineered algal biofuels requiring less energy for their production (compared to natural strains). There is opposition to genetic engineering in the European Union (EU) as well as in the US, with many opponents being insensitive to evidence and not liable to be influenced by arguments about risks and benefits. Yet, the authors found no evidence of possible concerns or opposition to genetically engineered algae, possibly because the media have not covered that subject much, so pertinent knowledge is not yet widespread.

Zavvanidou et al., (2009) analyzed the public acceptance of biofuels in Northern Greece. In their literature review, they found that 98% of US farmers would use biodiesel if prices were comparable to conventional diesel. US citizens thought they were well informed about ethanol and 78% of them agreed that *“using biofuels is a good idea”*. Turning to Canada, only 56% of Canadians had a (very) high knowledge of biofuels while only 22% of Canadians believed that biofuels are the most likely future source of transportation energy. While one third of Canadians were not willing to pay higher gasoline prices, two thirds were willing to pay a 1% higher sales tax to support the development of ethanol-based gasoline.

Seventy-three to 85% of Canadians were favorable to information campaigns and 42 to 56% of Canadians were favorable to mandatory ethanol-blended gasoline. Finally, in the UK, only 55% of its citizens knew what biofuels are and only 14% believed that biofuels are the best way to reduce emissions from road transport.

In their empirical survey, Zavvanidou et al. (2009) asked 571 urban respondents in the Thrace region of Northern Greece about energy sufficiency; energy savings (related to energy conservation); priority of biofuels (compared to other renewable energy sources); and willingness to use biofuels. 90.7% of respondents believed that climate change is related to the consumption of fossil fuels. 76.1% of respondents believed that energy savings should precede the use of alternative energy sources. 49.9% of respondents believed that the use of biofuels can be an effective solution against climate change. 53.9% of respondents believed that the use of biofuels can be an effective solution for the energy problem. Only 27.3% of respondents believed that priority must be given to biofuels compared to other renewable energy sources. Only 23.6% of respondents knew the difference between biodiesel and bioethanol. And while 80.9% of respondents were willing to use biofuels, only 44.8% were willing to pay a supplementary amount for their use.

74.4% of respondents in Thrace believed that an increase in farmer employment would be a very important advantage of (conventional) biofuels (Zavvanidou et al., 2009). 46.9% of respondents believed that product price increases are caused by biofuels. 75.5% of respondents worried about the energy sufficiency (related to the concept energy security) of Thrace, 83.7% of Greece, and 85.5% of the world, showing that concern increases with geographical scale. This concern probably reflects the situation in Greece, i.e. being a country with little production of fossil fuels, it has to import much of its energy. So, perhaps it would be good to frame algae as a solution for the energy problem at a global rather a regional scale.

Referring to conventional biofuels, 73.9% of respondents in Thrace thought that pollution caused by the intensive cultivation of energy plants was a very important disadvantage (Zavvanidou et al., 2009). 69.2% of respondents thought that the decrease of the environmental quality of biotopes and biodiversity due to the intensive cultivation of energy plants was a very important disadvantage. 76.5% of respondents thought that deforestation caused by the conversion of forested areas to agricultural land for the production of (conventional) biofuels was a very important disadvantage.

Respondents in Thrace with lower education were less likely to worry about energy dependence (Zavvanidou et al., 2009). Lower education people were also less concerned with international affairs, focusing instead on local issues; in this respect, they were like older people. Respondents who thought that the use of biofuels could be an effective solution to climate change were more probable to worry about energy dependence locally and regionally, but not globally. Car owners were more likely to worry about energy dependence in Greece, compared to non-owners. Older respondents were more likely to agree with prioritizing energy savings (compared to the use of alternative energy sources), possibly because they were more sensitive to expenses than younger people. Interestingly, respondents who believed that energy savings should precede the use of other energy sources, were more likely to believe that biofuels should be given priority compared to other renewable energy sources. So, for some people, algal biofuels may constitute an out-of-sight, out-of-mind type of renewable energy installations that may encounter less opposition from society.

Respondents in Thrace who found an increase in farmer employment to be a very important advantage of conventional biofuels, were more likely to choose biofuels compared to other renewable energy sources (Zavvanidou et al., 2009). Those respondents who thought that deforestation due the cultivation of biofuels was not a very important concern, also preferred the use of biofuels compared to other renewable energy sources. Interestingly, respondents with less education preferred the use of biofuels to other renewable energy sources. This could be caused by the fact that people who were less educated were farmers or in (a family related to) agriculture, so their support for conventional biofuels was simply support for their professional occupation. It could also be that people with more education were more aware of the advantage of other renewable energy sources compared with biofuels, which would mean that biofuels lack in public image (especially compared to other renewable energy sources) in the study area.

The willingness to use biofuels of respondents from Thrace was associated with their concern for climate change (Zavvanidou et al., 2009). People who believed in energy savings were also more willing to use biofuels, indicating that biofuels were seen as a form of energy conservation. As expected, respondents who preferred to use biofuels also believed that the degradation of biotopes and biodiversity due to the use of (conventional) biofuels was not very important. Correspondingly, respondents who believed that (conventional) biofuels degraded biotopes and biodiversity and were responsible for the increase of food prices, were unwilling to use biofuels. Finally, respondents who were more knowledgeable about biofuels were more likely to prioritize biofuels compared to other renewable energy sources. This indicates that education of the public on algal biofuel production might improve their acceptance by society.

4. Environmental aspects and sustainability

Like any human activity, both conventional and algal biofuels are characterized by environmental impacts which should balance with socioeconomic benefits. This section presents literature findings and discussed impacts that relate to the atmosphere and greenhouse gas emissions in particular; the lithosphere, i.e. land; the biosphere, in particular deforestation, ecosystems and biodiversity; the hydrosphere, i.e. water; wastes and recycling (which can affect negatively all other spheres); energy; health and accidents; and environmental sustainability.

The environmental dimension of large-scale algal oil production refers to negative impacts such as abuse of water resources; damage to waterways; soil pollution; soil erosion; land exploitation and degradation; interruption of animal habitat; algal blooms; eutrophication; biological invasion; and fish kills (Saad et al., 2019). Unfortunately, the environmental and social aspects of most technical works are rarely a part of technology development and licensing, being usually viewed as an afterthought once technical and economic issues have been resolved (Rösch and Maga, 2012).

4.1. Atmosphere

Turning to the atmosphere, conventional biofuels are not zero-emission (Chin et al., 2014). In fact, biofuels affect local air quality. The use of pesticides that are usually sprayed from air and the widespread practice of burning sugar cane fields result in atmospheric pollution (including particulate pollutants like smoke and ash) (Sawyer, 2008). Haze, another form of air pollution, has also been linked to the practice of using fire to clear harvesting residuals in plantations in South East Asia (Chin et al., 2014). Such environmental impacts are avoided by the production of algal biofuels.

On the cleanliness of biofuels, biodiesel is biodegradable and reduces sulfur and particulate emissions (Saad et al., 2019). Compared to fossil fuels, diesel produced from biomass produces smaller quantities of exhaust gases when burned ("Societal Benefits of Biofuels in Europe", n.d.). The use of ethanol blends has helped enable the removal of lead and other carcinogens from gasoline. It has been suggested that studies on the cleanliness of biofuels should also examine emissions of particulate matter and nitrogen oxides (Xi and Long, 2016).

4.2. Greenhouse gas emissions

Biofuels offer the opportunity of reducing or (at least) slowing the growth of carbon dioxide emissions from automobiles (Sawyer, 2008), but such effects differ from one generation of biofuels to the other. Compared to fossil fuels, conventional biofuels should reduce greenhouse gas emissions, but their comparison is not straightforward because many direct and indirect activities and processes must be taken into account ("Societal Benefits of Biofuels in Europe", n.d.). It has been argued that biofuels reduce net carbon emissions (Doshi et al., 2016), but this is debatable.

Biofuels have been touted as having big net carbon benefits via much lower greenhouse gas emissions. Theoretically, substituting biofuels for fossil fuels may mitigate climate change by releasing fewer greenhouse gases (Gonzalez, 2018). One of the problems with this argument is that calculations often do not account for the effect of land use changes (especially deforestation) which result from increased cultivation of biofuel crops. As carbon is emitted from clearing land, a long payback period may be required to achieve net emission reductions, as in the case of conventional biodiesel derived from palm oil in Southeast Asia and jatropha in Mozambique (Doshi et al., 2016). It has even been argued that some biofuels actually exacerbate climate change by releasing more greenhouse gases (Gonzalez, 2018).

In theory, biofuels should be greenhouse gas neutral because the carbon dioxide they release upon combustion is equivalent to the carbon dioxide they sequester from the atmosphere during cultivation (Gonzalez, 2018). Yet, some types of biofuel (e.g. biodiesel) lead to increased nitrogen oxide emissions which are greenhouse gases) (Xi and Long, 2016). The scientific community is uncertain as to the contribution of biofuels to the greenhouse effect, i.e. whether the carbon dioxide contributions of biofuels are positive or negative. There is evidence that mitigating effects are questionable.

Conventional biofuels in particular may generate more greenhouse gases than fossil fuels because of the clearing of forests and peatlands to plant them; the nitrogen-based fertilizers and petroleum-derived pesticides applied; the petroleum used by machinery used to cultivate and harvest them; and the energy required to convert the plants to fuel (Gonzalez, 2018). Greenhouse gases produced during the production of biofuels in technologically disadvantaged countries are much higher than that produced in technologically advanced countries (Xi and Long, 2016).

When considering the entire life cycle of many biofuels, it may be argued that their greenhouse gas emissions exceed those of fossil fuels (Gonzalez, 2018). The production and distribution of especially conventional biofuels requires considerable use of fossil fuels for the production of fertilizer; transportation of inputs and labor; manufacture and operation of farm machinery; processing of raw materials; and transportation of the final products to markets (Sawyer, 2008). There are also carbon dioxide emissions from the clearing of land and the decomposition of underground roots as well as emissions of nitrogen dioxide and nitrous oxide (both potent greenhouse gases) from the nitrogen that is present in fertilizers.

Contrary to the first generation of biofuels, the second and especially the third and the fourth generations of biofuels can potentially alleviate the greenhouse effect because of the nature of their feedstocks (Xi and Long, 2016). Algae is considered a sustainable fuel feedstock that can help decrease greenhouse gas emissions (Saad et al., 2019). In a recent study, 71% of experts thought that a partial replacement of fossil fuels with (genetically engineered) algal biofuels could help mitigate climate change (Villarreal et al., 2020).

While the manufacturing processes of algal biofuels can help reduce greenhouse gas emissions (Efroymson et al., 2017), their production is not yet economically feasible nor fully sustainable (Villarreal et al., 2020). To improve sustainability, if carbon dioxide is used as a carbon source, it is better to site algal cultivation near facilities that can provide adequate amounts of carbon dioxide (Saad et al., 2019).

By intensifying an industrial model of agricultural production, nations have adopted laws and policies that have exacerbated food security and contributed to climate change because the life cycle greenhouse gas emissions of many (first-generation) biofuels exceeds those of the fossil fuels they replace (Gonzalez, 2018). Environmentalists and governments agree that the response to climate change should not be limited to simply replacing fossil fuels with biofuels, but also attempting to change consumption patterns in developing countries in an effort to achieve carbon neutrality (Sawyer, 2008).

4.3. Land

For the last few years it has been argued that the benefits of conventional biofuels may be overstated (Doshi et al., 2016). The high price of biofuels has encouraged people to turn forests and pastures into farmland in order to cultivate conventional biofuels, thus increasing greenhouse gas emissions (Xi and Long, 2016). Cropland has expanded at the cost of natural ecosystems including rainforests (Rösch and Maga, 2012) which results in more greenhouse gas emissions caused by the loss of carbon sinks.

Xi and Long (2016) have argued that most studies show that the production of biofuel occupies land, damaging biodiversity, and impacting negatively both water consumption and water pollution. Furthermore, some countries use excessive fertilizer to promote the production of biofuels, polluting the soil and groundwater. Among other negative impacts, the production of conventional biofuels pressures local soil and water resources, limiting the water available for local consumption and food production; contaminating water supplies with pesticides and herbicides; and accelerating soil erosion because biofuels constitute monocultures (Gonzalez, 2018). Unfortunately, local land users are not consulted and environmental impact assessment is not conducted.

On the other hand, algae can convert up to 3% (Gomiero, 2015) or even 5% of the sunlight energy to biomass, so land use efficiency is higher than with traditional crops that use photosynthesis with an efficiency ranging between 0.5 and 1% (Rösch and Maga, 2012). In comparison to conventional biofuels, in the case of algal biofuels the reduced demand for arable land negates the need for widespread conversion of forests and woodland, reducing negative impacts on carbon sinks and biodiversity (Doshi et al., 2016).

4.4. Deforestation

Xi and Long (2016) argued that converting rainforests, peatlands, savannas, and grasslands to arable land for growing conventional biofuels creates a carbon debt, i.e. releases more carbon dioxide than the amount saved when the produced biofuels replace fossil fuels. Only the conversion of degraded or abandoned agricultural land would not create a carbon debt. The loss of maturing forests and grasslands in particular nullifies future sequestration gains, creating a carbon debit (Gonzalez, 2018). Furthermore, planters and palm oil producers may prefer the traditional landfill and fire clearing practices instead of collecting residues for the production of biofuel (Chin et al., 2014). There is also concern that clearing forests to plant energy crops, releases the carbon stores in plants, trees, and the soil, increasing greenhouse gas emissions ("Societal Benefits of Biofuels in Europe", n.d.).

Deforestation accelerates forest dieback (a plant disease); edge effects; increased flammability; multiplication of sources of ignition; and feedback loops driving higher temperature and lower humidity. In other words, anthropogenic climate change interacts with deforestation (Sawyer, 2008). In other words, deforestation is linked with dieback, which – assisted by climate change – results in economic losses, social unrest, and political instability. Deforestation is also associated with underlying poverty; subsistence farming; logging; cattle ranching; and commercial food production ("Societal Benefits of Biofuels in Europe", n.d.).

In Brazil, the expansion of sugarcane, soybean and animal feed production for biofuels have contributed to the clearing of areas of the Amazon rainforest and tropical savannahs (Xi and Long, 2016; Gonzalez, 2018). In addition, the expansion of sugar and cane monocultures displaces cattle-raising to frontier areas where land is usually much cheaper, generating further pressures for deforestation (Sawyer, 2008). The production of biodiesel from soya beans and the production of ethanol from sugarcane or maize will have negative impacts on the Amazon and other tropical biomes, interacting with climate change which may cause dieback or reduction of the Amazon forest to shrub. Deforestation in Brazil has been associated with a boom in soya (after 1990) and beef (after 2000), primarily for export to global markets. In Asia, deforestation is carried out to make space for oil palms (Xi and Long, 2016). Unfortunately, efficient large-scale production of carbohydrates and oils presupposes monocultures, which lead to conversion of land from pasture to crops and further deforestation (Sawyer, 2008).

Compared to conventional biofuels, it is estimated that between approximately one third and half of proposed current and future algal production would overlap non-forested ecosystems and agricultural lands, i.e. mainly grasslands and mixed forest areas (Correa et al., 2021). Therefore, algal biofuels may well play an important role in mitigating the dramatic interaction of biofuels with deforestation and its associated impacts.

4.5. Ecosystems and biodiversity

Conventional biofuels affect ecosystems and biodiversity. Biofuel crop plantations like sugarcane and soya are large-scale homogeneous monocultural landscapes, leading to simplified ecosystems that can be easily damaged (Xi and Long, 2016). Such monocultures replace biodiverse, carbon-rich ecosystems (Correa et al., 2021) and have direct ecosystemic effects on biodiversity, soils, water resources, and the atmosphere (Sawyer, 2008) as well as direct and indirect effects on climate change (Gonzalez, 2018). The negative impacts of biofuels on biodiversity include multiscale effects on genetic, species, and ecosystem diversity (Xi and Long, 2016). The production of conventional biofuels from willows, rapeseed, and elephant grass may reduce the number of wild animals; destroy landscapes and historical sites; and degrade soil and water quality. At the species level, habit fragmentation and bioinvasion may result in habitat pollution, degradation, and disturbance. Another concern is that the production of biofuels may damage ecosystems (e.g. losses of soil organic carbon) and thus reduce yields. Pesticides used by first-generation biofuels have also had environmental impacts.

The biodiversity of an ecosystem may be measured by the number of (threatened) vertebrate species; the number of vertebrate species with small distribution ranges; the presence of islands; the presence of areas with low human pressures on the environment; and the presence of mangroves (Correa et al., 2021). Biodiversity is greatly reduced when forest or savannah land is cleared (Sawyer, 2008) and also reduced when mixed farming systems are replaced by monocultures. Soil fertility is also affected by the contamination, compaction, and loss of organic matter that occurs when the natural vegetation is removed.

Conflicts between the cultivation of conventional biofuels, agriculture, and biodiversity can push towards more sustainable modes of biofuel production (Correa et al., 2021) like algal biofuels. The impacts of conventional biofuels on biodiversity vary with feedstock (Xi and Long, 2016). Compared to algal biofuels, the production of biofuel from forest residues causes more negative impacts on biodiversity. Algae may be cultivated on non-arable or marginal land, relieving the pressure on biodiversity (Rösch and Maga, 2012). To this end, it has been suggested that alternative measures of land use (e.g. based on ecosystem services or economic alternatives such as tourism or mining) may be considered in selecting optimal locations for algal biofuel production systems (Correa et al., 2021). The production of algal biofuels may be developed in areas of biodiversity value lower than the global median value such as those is North and East Africa; the Middle East; western South America; the Caribbean; and Oceania. Some unlikely impacts of genetically modified algae may have to be taken into account, e.g. (accidentally) released algae altering natural ecosystems (Efroymson et al., 2017).

4.6. Water quantity and quality

The impacts of biofuels on the hydrosphere relate to water consumption and water pollution (Xi and Long, 2016). Biofuel development may have adverse effects on forest surface water and groundwater (Xi and Long, 2016). The risk presented may be proxied by exposure indicators such as the proximity of cultivation systems to steams or groundwater, which relate to risks to aquatic organisms or humans that drink the water (Efroymson et al., 2017).

Overall, the water consumption of ethanol-powered cars is such that if the US continued to promote bioethanol, its freshwater resources would be threatened (Xi and Long, 2016). Cane production and processing require as much as four liters of water for every liter of ethanol (Sawyer, 2008). Water allocation is also a concern because the cultivation of biofuel feedstock is water intensive (Doshi et al., 2016). Water needs may even be higher than natural replenishment rates for aquifers in countries like the US and Brazil.

Water pollution may be one of the reasons for opposing biofuel development (Chin et al., 2014) but water consumption for the production of biofuels varies with processing technology (Xi and Long, 2016). Algal biofuels are characterized by higher biofuel productivity per unit area and do not depend on fertile lands or freshwater, so they could be developed on lands that are unsuitable for agriculture or have low biodiversity value (Correa et al., 2021).

Water availability and use have been considered for the case of algal biofuels (Efroymson et al., 2017), with their demand for water and their emissions during processing being considered negative impacts (Rösch and Maga, 2012). The amount and quality of water needed for the cultivation of algae depends on the cultivation technology (open ponds or closed reactors) and the ability of the specific species to grow in saline or wastewater. Using seawater decreases freshwater requirements for the production of biofuels (Xi and Long, 2016), but the use of saltwater is limited to marine algae (Rösch and Maga, 2012). On the other hand, if saline water was leaked (e.g. from a pond in an algal biofuel production facility), nearby freshwater aquifers could be contaminated (Efroymson et al., 2017). And landlocked countries do not have the opportunity to use seawater so that they can limit the consumption of freshwater resources (Correa et al., 2021).

Fresh water is added to open ponds during the summer (to prevent evaporation from creating excessive salt concentrations), so the cultivation of algae in open ponds can stress local water resources in warm climates and arid areas (Rösch and Maga, 2012). Water demand is lower in photobioreactors. Nevertheless, algae are characterized by reduced competition for water, given that they are preferably cultivated in wastewater (Doshi et al., 2016). Algae production systems have a great potential for water remediation through the consumption of nutrients from wastewater and their usage of (free) carbon dioxide emitted from industrial or agricultural operations (Correa et al., 2021).

With the fourth generation of biofuels, risks are related to the possible uncontrollable release of genetically engineered algae to the hydrosphere (Villarreal et al., 2020). Such concerns pertain to the spread and invasiveness of genetically modified biofuels with pests growing resistant to transgene products (Wegener and Kelly, 2008).

4.7. Wastes and recycling

Non-industrial private forest owners may be willing to collect woody biomass for the production of conventional biofuels, even for free (Chin et al., 2014). Contrary to the land-based production of biomass, the closed-production nature of algae allows for controlled use, recycling, and disposal of chemicals (Rösch and Maga, 2012). Large-scale algal cultures and agriculture require the same amount of nutrients (Saad et al., 2019). Fertilization in algae cultivation is performed in closed systems, so no nutrients are released to the environment (Rösch and Maga, 2012). Algae also provide ecosystem services such as the recycling of carbon dioxide and the phytoremediation of wastewater, removing any nutrients.

The use of wastewater by algal biofuels prevents their competition for water with food and feed crops and provides nitrogen and phosphorus (Saad et al., 2019; Rösch and Maga, 2012). Algal biorefinery systems can use free sources of carbon dioxide (e.g. from industries and anaerobic digesters) and nutrients (e.g. from agricultural residues and wastewater) (Correa et al., 2021). A drawback of wastewater is that it may contain algal pathogens; predators; heavy metals (e.g. lead, mercury, arsenic, cadmium); and other toxic contaminants, which may be absorbed by algae. Especially in Japan, biofuels seem useful for recycling waste materials, although in some cases biofuels compete with alternative uses for recycling the wastes.

4.8. Energy

Renewability and cleanliness are two important characteristics for biofuels (Xi and Long, 2016). Biofuels are considered a renewable energy resource, whose cleanliness may be measured by their emissions of carbon dioxide and other pollutants, and their impacts on water resources and biodiversity. Yet, it has been argued that their renewability, cleanliness, resource, and environmental friendliness are not as positive as expected (Xi and Long, 2016). On the one hand, some Life Cycle Analysis studies have confirmed that conventional biofuels are renewable (because they provide energy through photosynthesis). On the other hand, other studies question their renewability, focusing on the fact that the consumption of nonrenewable energy in the life cycle process of biofuels depends on conditions such as resource endowment; geographical and natural conditions; economic situation; and technology level. Discrepancies among studies examining the cleanliness of biofuels are caused by the fact that these studies are done in countries that are at different stages of development; or that they examine different types of biofuels; or because cultivation methods differ; or that researchers use difference methods for calculating carbon dioxide emissions.

It has been argued that resource conservation may be measured by indicators such as depletion of nonrenewable energy resources (e.g. petroleum) and the fossil fuel return on investment (Efroymson et al., 2017). Algae are a reliable decentralized source of renewable energy (Rösch and Maga, 2012). The renewability of an energy source depends on the amount of (nonrenewable) fossil energy consumed in the entire life cycle of the energy source, including exploration, production, transportation, use, pollution treatment, etc. (Xi and Long, 2016). Although algal biofuels are characterized by several favorable environmental impacts, some Life Cycle Assessment studies (as mentioned before) have indicated that algae production processes (mixing, harvesting, dewatering, extracting, and refining) are extremely energy intensive, making it difficult to achieve a positive energy balance (Rösch and Maga, 2012).

4.9. Health and safety

Health and safety concerns are important factors with energy sources including biofuels. The substitution of renewable energy (like biofuels) for fossil fuels may have indirect beneficial effects on human health, e.g. by improving indoor air quality. On the other hand, nitrogen emissions from combustion engines, which are higher in the case of biodiesel, can cause lung cancer (Chin et al., 2014).

Few types of health issues and injuries are specific to the production of algal biofuels (Efroymson et al., 2017). These include algal mass dried without mitigating airborne particulate matter; use of unfamiliar toxin-producing algae; risk from volatile organic compounds emitted from unventilated algal cultivation systems; and the use of wastewater or waste carbon dioxide streams that lead to the accumulation of metals. Contamination by bacteria and algae is also a challenge in the case open pond systems (Saad et al., 2019). On the other hand, positive effects on human health may be achieved by substituting algal biofuels for fossil fuels, although these are lessened by the use of fossil fuels for the algae production and the use of toxic substances (e.g. for cleaning reactors and extracting lipids and other high-value substances from algae) (Rösch and Maga, 2012). Finally, regarding the safety of society at a larger scale, catastrophic events are defined as accidents involving more than 10 human fatalities, affecting an area greater than 1000 hectares or leading to the extinction or extirpation of a species (Dale et al., 2013), which are rather unlikely at least for small and medium scale algal biofuels installations.

4.10. Aesthetics and sustainability

Sustainability has economic, environmental, and social components (Efroymson et al., 2017) and it has been suggested that a holistic sustainability approach is required for the implementation of successful large-scale algal biofuel production projects (Rösch and Maga, 2012).

Environmental sustainability refers to water quality and quantity; soil quality; air quality; greenhouse gas emissions; biodiversity; and (ecosystem) productivity (Efroymson et al., 2017). Energy, carbon, land, and water footprints have been considered criteria of sustainability (Rösch and Maga, 2012). Social and economic sustainability indicators are associated with one another, e.g. public opinion influences profitability (Efroymson et al., 2017), and affected by environmental conditions, e.g. cold-weather shutdowns reduce greenhouse gas emissions, but also increase costs.

Social sustainability considers social well-being; energy security; external trade; profitability; resource conservation; and social accessibility (Efroymson et al., 2017). Selected principles of sustainable development may be related to public acceptance and include: protection of human health (referring to use of dangerous chemicals, changes in life expectancy, etc.); securing the satisfaction of basic needs (such as supply of food supplements, feed for agriculture, feed for terrestrial animals, and renewable energy); creating new jobs; having equitable access to natural resources; reducing extreme income and wealth inequalities; avoiding technical risks with potentially catastrophic impacts; having equal access to education and occupation; participating in social-decision making process; preserving cultural heritage and diversity; conserving social resources (such as tolerance and solidarity) (Rösch and Maga, 2012). With conventional biofuels, small subsistence-based farm production is usually replaced by capital-intensive, export-oriented industrial farms that tend to diminish local food availability and reduce local employment (Gonzalez, 2018). This way, they exacerbate poverty; pollute the local water supply with pesticide and fertilizer runoff; accelerate soil erosion through intensive cultivation; intensify greenhouse gas emissions; and reduce the availability of local water (also needed for irrigation).

Aesthetics impacts such as visual intrusion may also affect sustainability. The clearing of land and forests for the cultivation of conventional biofuels may trigger concerns for aesthetic and environmental issues (Chin et al., 2014). On the other hand, only large-scale algal biofuel production plants are likely to affect the *"sensual, contemplative, spiritual, religious and aesthetic experience"* of a landscape (Rösch and Maga, 2012).

Promoting sustainability standards for biofuels would allow stakeholders to demonstrate that their production methods are sustainable, taking into account local conditions (Elder et al., 2018). Biofuel producers should take sustainability into account when making decisions about siting, cultivation, logistics, conversion, and fuel blends (Efroymson et al., 2017). Choices related to the steps of the supply chain should be informed by sustainability indicators. As an example, biofuel logistics involves choices (such as blend conditions or engine type) related to transport; storage; coproducts; and biofuel end uses (Efroymson et al., 2017). Consumers also take sustainability into partial account when deciding about biofuel purchases.

When researchers include all the direct and indirect impacts of biofuels, it may be concluded that first-generation biofuels are more damaging to the environment than fossil fuels (Gonzalez, 2018). In fact, first-generation biofuels may release more greenhouse gases than fossil fuels due to the unsustainable practices employed in their production (Gonzalez, 2018). The expansion of first-generation biofuels will impair food security, particularly in developing economies; degrade native ecosystems; and exacerbate global warming (Correa et al., 2021). Second-generation biofuels, which are based on the transformation of lignocellulosic compounds, also compete with agricultural lands; reduce soil carbon stocks (as biomass residues are extracted from crops and forests; and drive the transformation of biodiverse areas mainly in tropical countries with weak governments.

Third-generation biofuels are considered a more sustainable alternative to first and second generation (Correa et al., 2021). The choice of algal strains is a time-consuming and tedious challenge that must take into account environmental conditions, but algal biofuels are characterized by few negative impacts on the environment (Saad et al., 2019).

4.11. Ethical aspects

Biofuels are characterized by some interesting ethical aspects. A great review of related issues was carried out by Gonzalez (2018) who provided a critical view of conventional biofuels from the standpoint of environmental justice. Environmental justice implies equitable access to food, water, land, and energy; focuses on impacts on vulnerable populations; and combats poverty and racism.

4.11.1. Food

Many conventional biofuel feedstocks can be used as both food and fuel, so an important concern of conventional biofuels is their impact on the fundamental right to food. One of the ethical obligations of states (implied by global declarations) is to not interfere with the means of subsistence of their population (Gonzalez, 2018). Such ethical issues that relate to the production of conventional biofuels are not associated with the production of algal biofuels.

4.11.2. Environmental injustice

Environmental justice is grounded in global rights, including the aforementioned fundamental right to food (Gonzalez, 2018). To respect the right to food, states must not deprive people of their livelihood. In this respect, states must take measures to prevent third parties (such as foreign investors) from depriving people of the means to grow or purchase food. States must also prevent economically powerful parties from displacing small farmers from food production. Furthermore, states must provide vulnerable populations with jobs or with the resources to grow or purchase their own food.

The laws and policies for conventional food-based biofuels of the US and the EU have caused environmental injustice by affecting negatively the right to food of poor people; increasing food prices; and triggering large-scale land acquisitions that limit the access of local communities to land, water, and food (Gonzalez, 2018). While these policies do not mitigate climate change, they facilitate a global transition to fossil-fuel based industrial agriculture, which favors export-oriented corporate agribusiness (at the expense of local farmers and food production) and degrades local ecosystems.

Conventional biofuels contribute to distributive injustice because they create benefits that are reaped by commercial lenders, financial speculators, oil companies, agribusiness corporations, and affluent consumers (Gonzalez, 2018). These costs are borne disproportionately by low-income, food-insecure populations who are faced with rising food prices and eviction from lands that were traditionally theirs to farm, forage, and graze. Conventional biofuels are also associated with procedural injustice because the US and the EU mandates are implemented without an adequate assessment of their environmental and socioeconomic impacts, which are predominantly borne by low-income communities of the Global South. Finally, conventional biofuels are also characterized by corrective injustice because the affected communities often have limited or no legal recourse to seek compensation for rising food prices (which compromise their right to food) and land grabbing (as they are evicted from their lands). These types of injustice are largely avoided by the production of algal biofuels.

The perspective of environmental injustice links environmental degradation with vulnerable populations, affecting social ills such as poverty, racism, and gender discrimination. As mentioned before, contrary to the cultivation and production of conventional biofuels in the Global South, the production of algal biofuels is not preferential to work by women and children.

4.11.3. Policies and ethics

As part of their effort to welcome foreign investors (and increase their personal wealth and power), government and local elites frequently do not hesitate to evict local residents (Gonzalez, 2018). Unfortunately, local communities typically lack legal recourse to prevent dispossession or receive compensation, because national laws oftentimes assign the ownership of rural lands to the government or customary chiefs rather than the communities that exploit the land. To make matters worse, international investment agreements often eliminate redress options and worsen inequity by protecting the assets of foreign investors from government actions that might diminish their value (even bypassing the domestic legal system). Furthermore, such provisions deter the enactment of labor, health and safety, environmental, and human rights legislation that would enable claiming compensation.

The offshore cultivation of biofuel feedstocks replicates the outsourcing of economic activity to the Global South in order to take advantage of lower labor costs; weak environmental standards (related to the pollution haven hypothesis); and the imposition of social and environmental externalities on vulnerable social communities with limited capacity to react (Gonzalez, 2018). It was suggested that the biofuel policies of the US and the EU produce environmental injustice in the Global South by *“ravaging local ecosystems, depressing food production, and depriving vulnerable communities of access to land and water necessary to produce food.”*

This way, conventional biofuel policies are intertwined with social injustice as the already rich Global North gets richer at the expense of the vulnerable Global South (Gonzalez, 2018). Essentially, the responsibility of mitigating climate change is transferred to the poorest people in the world. Eventually, the US and the EU will have to erect regulatory barriers to the expansion of conventional biofuels, addressing the issues related to human rights and environmental justice.

5. Policy and geopolitical aspects

This section presents and discusses biofuel literature findings related to country policies; socioeconomic, ecological, food, transportation and energy security; and geopolitical considerations.

The larger social context of biofuels encompasses economics; public policies; structural matters associated with legislators, regulators, producers, and marketers of biofuels; as well as politics of support or opposition of biofuels by political parties, policy makers, and NGOs (Wegener and Kelly, 2008). Algal biofuels have long-term economic benefits; may benefit from government support and partnerships with universities and research institutions; and should be supported with policies (Doshi et al., 2016; Correa et al., 2021).

Algal biofuels can help meet the energy demand of transportation, but this argument makes sense only as long as a positive energy balance is achieved during the production of algal biofuels (Rösch and Maga, 2012), an objective in which Chevron, BP, and ExxonMobil have made great investments. On the consumer side, the adoption of flex-fuel engines places consumers in the role of investors, as they consider purchasing more expensive flex-fuel engine vehicles so that they may enjoy the benefits of cheaper fuel in the long run (Chin et al., 2014).

A concern is that the use of conventional biofuels (as an alternative energy source) cannot guarantee an effective energy supply because of uncertainties related to regional climate, soil, water, and other uncontrollable natural factors (Xi and Long, 2016). In this sense, conventional biofuels have similarities with wind and solar.

5.1. Policies

In this section, issues related to policies, investments and the involvement of the public are discussed.

Doshi et al. (2016) highlighted economic and policy issues surrounding conventional biofuels; and outlined the benefits and limitations of algae as an alternative feedstock. It was argued that the development of conventional biofuels has benefited from direct and indirect policy interventions. Directly supportive policy measures have included: tax concessions; reduced fuel excises; and subsidies for production and infrastructure. Indirectly supportive policy measures have included: biofuel blending mandates; and trade measures protecting domestic biofuel industries from lower cost foreign suppliers. The challenge is to find a policy mix that provides incentives for algal biofuels while transitioning away from conventional approaches and minimizing risks.

Compared to other alternatives for farmers, conventional (especially second-generation nonfood) biofuel crops present limited alternative uses and are not attractive options without economic support from the government (Elder et al., 2018). The support of policy makers also provides a favorable climate for the development of innovative technologies (Chin et al., 2014). Criteria denoting a supportive biofuel policy framework include: consistency of policies; clear objectives of policies; functional government agencies; community involvement in the placement of projects; favorable financial system; and research and development opportunities. Policy makers should be aware of global trends so that local impacts may be mitigated without missing opportunities (Sawyer, 2008). The opinion of policy makers is reflected in existing biofuel policies (Chin et al., 2014).

Energy policies address supply side management (SSM) and demand side management (DSM) (Xi and Long, 2016). On the one hand, SSM is a top-down process intended to influence energy producers to ensure sufficient supply of energy and focus solutions of supply-demand discrepancies on the supply side. SSM comes in two primary forms: alternative energy (i.e. seeking to achieve diversification of energy sources); and alternative trade (i.e. importing energy and transferring industries). On the other hand, DSM is a bottom-up process that employs economic, legal, technical, and other measures to regulate the behavior of users; improve the efficiency of energy use; and reduce dependence on energy-intensive industries. DSM compensates for the approach of SSM by promoting the self-renovation of energy industries. Most biofuel policies are considered to fall within the purview of SSM.

Government policies and problems that support biofuels are mainly focused on technical improvements and commercial scaleup (Chin et al., 2014). Second and particularly third-generation biofuels imply the adoption of new production technologies. Fourth-generation biofuels can potentially address technical and environmental concerns, but bring regulatory hurdles (Villarreal et al., 2020). In any case, parties still in the payback period of projects involving first-generation biofuels would resist (Chin et al., 2014).

The building of a regulatory system is likely to depend on both public and political perceptions of new technologies (Wegener and Kelly, 2008). It has been suggested that rather than viewing the production of food, biofuels, and non-food products as competing activities, it may be more beneficial to consider developing synergies among these sectors (in terms of technology, land use, and economics) (“Societal Benefits of Biofuels in Europe”, n.d.).

Gonzalez asserts that the success of the conventional biofuels industry is a testament to the power of well-organized lobbying by powerful corporations (2018). Industry players in the biofuels sector include large-scale plantation companies, engine manufacturers, and oil companies (Chin et al., 2014). Local governments may provide incentives to entice companies to engage in or relocate to an area to provide employment (Efroymson et al., 2017).

Risk financing for pioneer projects (such as those of algal biofuels) could require higher interest rates than future projects with proven technologies (Efroymson et al., 2017).

Profitability will be different for the first few plants than after many plants are built and operated.

Since the 1970s, the rapid increase of biofuel production in the US and globally has been driven by powerful corporate interests (Gonzalez, 2018). Despite the questionable climate benefits of conventional biofuels, both the US and the EU have supported and promoted them with subsidies, tax exemptions, and mandates for blending into transportation fuels. This was in part motivated by the conviction that, in some cases, simply waiting for the development of a commercially viable product may be too late (Wegener and Kelly, 2008). Delays and uncertainties could deter investments. Regulatory arrangements have to be implemented that hasten economic viability.

Large investments are favored by security and political stability, but are not devoid of negative socioeconomic impacts. For example, sugarcane plantations (as in Cuba) involve large long-term investments that boost the economy, but are themselves socially unstable and disruptive (Sawyer, 2008).

Regarding the role of the public in algal biofuels, the public could participate in decision making on research programs; public expenditures; development and demonstration; and finding suitable locations for algal production facilities (Rösch and Maga, 2012). Public involvement in biofuels should benefit information and knowledge delivery; project sustainability; and satisfying different social groups (Chin et al., 2014). Public engagement may depend on the willingness of local authorities and project owners to allow the public to participate. Also, local involvement in the development of biofuels may be assumed as representing passive consent.

Stakeholder workshops and online questionnaires could be used for assessing the social aspects of sustainability for algal biofuel development (Rösch and Maga, 2012). The public may have concerns, e.g. that excess supply from genetically modified plants (e.g. oil palms) may be (surreptitiously) channeled to the production of food (Chin et al., 2014).

Gonzalez (2018) argued that the biofuel boom was sparkled (to a large extent) by government policies. Reducing fossil fuels subsidies would serve to make agricultural prices more closely linked to fuel prices and thus create a more level playing field for biofuels (Elder et al., 2018). Deriving fuel from biomass and reducing the dependence on imported fossil fuels would help stabilize the cost of transport fuels, protecting consumers from severe fluctuations in the price of oil ("Societal Benefits of Biofuels in Europe", n.d.).

Significant percentages of food crops have been diverted to the production of first-generation biofuels, a trend that is likely to continue being supported by mandates (Gonzalez, 2018). The key limitations of conventional biofuels relate to the food versus fuel debate (Doshi et al., 2016). Algal biofuels address these concerns, but are constrained by high production and energy costs. Therefore, policy interventions are likely to have a major influence on the further development of algal biofuels at least in the near future.

5.1.1. Countries and policies

Turning now to the policies of specific areas and countries, it is thanks to policy support that biofuels have infiltrated markets such as: corn-based ethanol (biopetrol) and soybean-based biodiesel in the US; sugarcane ethanol in Brazil; and rapeseed biodiesel in Europe (Doshi et al., 2016). There has been aggressive government promotion of biofuels in the US and the EU, which has benefitted corporations that invest in biofuels research (including Shell, ExxonMobil, Dow, Monsanto, DuPont, and Syngenta) (Gonzalez, 2018). Gonzalez (2018) has asserted that in the US and the EU, subsidies instituted in the name of environmental protection have been a guise for the transfer of wealth from taxpayers to agri-food and energy corporations. The Renewable Energy Directive of 2009 established sustainability criteria for biofuels, but these were purely environmental and did not address the social and human rights impacts, including their impact on the right to food. This was in part corrected in 2015, when the European Parliament imposed a 7% cap on the contribution of food-based biofuels to the EU mandate.

In the US, up to 40% of corn price increases have been found to be the result of ethanol mandates (Doshi et al., 2016). This makes food less affordable and increases world hunger. Nevertheless, increasing oil prices, unpredictable weather patterns, increasing populations, and investment speculation may have larger impacts on food prices. Elsewhere, land grabs hasten the South's transition to large-scale, capital-intensive industrial agriculture (Gonzalez, 2018). This goes contrary to the effort of scientists and policy makers to promote small-scale sustainable agriculture in food-insecure countries in an effort to fulfil the right to food and address climate change.

Studies of algal production have been carried out in the EU, US, Sicily, Australia, Brazil, Chile, Mexico, Colombia, Ecuador, Panama, and Venezuela, and Iran (Correa et al., 2021). The governments of China, India, Indonesia, and Japan have also engaged in research and testing of alternative feedstock and second-generation biofuels (Elder et al., 2018). As mentioned before, although many conventional biofuels have high production costs and uncompetitive retail prices, policy support (like blending mandates and tax credit) has enabled some types to enter the consumer fuel market, e.g. sugarcane ethanol in Brazil (Doshi et al., 2016). While the global population is increasing, arable land is limited, which suggests that conventional biofuels are unsustainable. In countries like Brazil, sprawling settlement patterns and trade networks mean that transportation logistics will continue to dictate the expansion of agroenergy production (Sawyer, 2008). The demand for arable land translates to mass deforestations (as in South Asia for palm oil or Brazil for sugarcane and soybeans) which result in losses in ecosystem diversity. Even second-generation feedstocks may affect land for food and fodder in poorer rural communities.

Considering China, India, Indonesia and Japan, Elder et al. (2018) concluded that biofuel promotion policies in different countries have similar objectives but different emphases. These four countries emphasized rural development, but while Japan placed more emphasis on reducing greenhouse gas emissions, the other three prioritized energy security. Surprisingly, major aspects of biofuel policies have converged, despite significant differences among these countries. All four countries recognized that overdependence on one or few feedstocks is undesirable.

Further implications may be drawn from the examination of biofuel policies in China, India, Indonesia, and Japan (Elder et al., 2018). Adopting a cautious stance and avoiding setting unrealistic targets is a good strategy. A large-scale rapid expansion of biofuels (which would pose great risks for the food-fuel conflict) may be limited by the availability of land, water and labor. If targets were not met by domestic production, imports would be necessary. High targets would encourage unsustainable production; deforestation; water shortages; food-fuel conflict; and appropriation of land used by poor people.

China, India, Indonesia, and Japan have had to deal with the question of how much should biofuels be promoted through special economic incentives (such as subsidies), mandatory targets or price regulations (Elder et al., 2018). This is especially important in countries where many sectors (particularly fossil fuels) receive special treatment, like India and Indonesia. In an environment where state support is given to many industries, a lack of special promotion measures effectively works like disincentive policies. Supportive measures cannot be justified easily in the case of (conventional) biofuels, because their social benefits are not clear-cut.

Contrary to China and Japan, India and Indonesia backed off initial targets that were overambitious (Elder et al., 2018), reflecting the concern of their governments about the food vs fuel conflict. Indonesia in particular hopes to become the Middle East of biofuels, but palm oil is too important for food for the government to allow significant diversion to other uses. Environmental protection groups in Malaysia have lobbied to boycott palm oil products which they consider to be associated with forest clearing and animal extinctions (Chin et al., 2014). Malaysia's National Biomass Strategy 2020 delivered a future roadmap for the development of second-generation biofuels, using residues from the palm oil industry. A winter palm biodiesel was invented, able to operate at temperatures as low as −20°C without clogging diesel engines.

In Malaysia, the market penetration of palm-based biodiesel is backed with government subsidies, but subsidization is not a long-term sustainable strategy for driving the incremental usage of biofuels (Chin et al., 2014). Regarding blended fuels, oil companies are concerned that high purchase prices will dissuade customers and thus affect their financial performance. It was because of this that the Malaysian government agreed to subsidize biodiesel.

5.2. Security and geopolitical aspects

Like other energy sources including renewables, biofuels also have geopolitical repercussions, which interact with their socioeconomic and political aspects. This section examines how (algal) biofuels interact with socioeconomic, ecological, food, transportation, and energy security. The section is rounded up with some geopolitical considerations.

Since the oil shocks of the 1970s, biofuels and other alternative energy sources have entered a golden stage of development (Xi and Long, 2016) in the hope that they will not be susceptible to the geopolitical challenges that have plagued fossil fuels for decades (Efroymson et al., 2017). Biofuel production is experiencing a rise in both developed and developing countries including the US and China (Xi and Long, 2016). Brazil, the US, France, Sweden, and Germany are leaders in the development of biofuels (Saad et al., 2019) while Malaysia is the leading nation in the production of palm-based biodiesel (Chin et al., 2014).

5.2.1. Socioeconomic security

Regarding beneficial and harmful impacts on socioeconomic security, for developing countries (like Brazil), biofuels offer promises of employment; income; foreign investment; regional development in depressed areas; tax and foreign exchange revenue; and exporting technology and know-sale to areas like Africa (Sawyer, 2008).

Elder et al. (2018) discussed the social and economic impacts of conventional biofuels in three large Asian rapidly developing countries (China, India, and Indonesia) and one developed country (Japan). Potential positive impacts (for China, India, Indonesia and Japan) were expected in employment, income, rural development, air pollution, and energy security. Rural electrification and improved energy access for poor people are important objectives for developing countries. Potential negative impacts included: competition with food and other land uses; impacts on ecosystem services (caused by deforestation and water usage); and social impacts such as land tenure rights, e.g. when the land of poor farmers is taken over by large producers without fair compensation.

The case studies of China, India, and Indonesia showed that biofuels are unlikely to be miracle cures promoting rural development (Elder et al., 2018). Furthermore, the idea of growing nonfood crops in wastelands would require significant inputs of water and fertilizers. Not to mention that wastelands provide ecosystem services and are used by lower income people for economically viable purposes.

Biofuels also generate questions about costs and risks, especially in the global South (Sawyer, 2008). In this respect, algal biofuels can act like a hedge against the price volatility of other fuels, especially in countries with high fuel imports (Efroymson et al., 2017).

5.2.2. Ecological security

Turning to ecological security, there has been concern about managing to avoid the environmental impacts of unplanned biofuel expansion globally and especially in the Global South (Correa et al., 2021).

The expansion of the cultivation of conventional biofuels to satisfy US and EU demand impacts negatively the countries of the Global South, polluting and depleting water supplies, and exacerbating deforestation thus climate change (Gonzalez, 2018). In Indonesia and Malaysia, tracts of tropical forest and peatland have been converted to plantations. Middle-income southern nations like China, India, Brazil, and South Africa have also played a significant role in the global land rush, generating tensions among southern nations.

The revolution of biofuels has granted Brazil and other tropical countries in the global South a new role as agroenergy hegemon producers, because land and labor are cheap and climatic conditions favor photosynthesis all year round (Sawyer, 2008). Transboundary issues have emerged in some cases, as in the case of forest fires in Indonesia, which were intended to clear land for pulpwood and oil palm, polluting neighboring countries like Singapore, Thailand, Malaysia, and the Philippines (Gonzalez, 2018). In turn, Indonesia has blamed Singapore and Malaysia oil palm consortiums for haze pollution caused by forest fires (Chin et al., 2014).

Using algae for the production of biofuels would have important beneficial effects on ecological security. Less than 1.1% of the global terrestrial surface would be required to fulfill 30% of the future domestic transport energy demand, requiring lands with relatively low agricultural and biodiversity value, with little dependence on freshwater resources (Correa et al., 2021). Approximately one third of proposed algal production areas would overlap with mixed forests, croplands, grasslands, natural vegetation mosaics, and woody savannas. Nevertheless, areas that are better suited for food production or having high biodiversity would be spared.

5.2.3. Food security

Various studies have examined the association of conventional biofuels with food security at an international, national, and local level (Xi and Long, 2016). The feedstock of both first and second-generation biofuels (based on agricultural products and cellulose correspondingly) was found to compete with the production of food in China and Japan. During the global food price crisis of 2008, which was caused by the dependence of the global food system on a few commodity traders, risks were posed particularly to small farmers and food-importing southern nations (Gonzalez, 2018).

Percentage change in fuel price volatility may be an appropriate indicator describing food security (Efroymson et al., 2017). Middle-income southern countries (like China, India, Saudi Arabia, Qatar, and South Korea) have invested in the offshore production of food to help them offset price volatility in international food markets as well as domestic scarcity of fertile land and irrigation water (Gonzalez, 2018).

Problems like competition with agricultural crops for land or increase in food prices affect food security and may be addressed with biofuel policies (Chin et al., 2014). It is among the obligations of states to not interfere with a population’s means of subsistence and take measures to eliminate malnutrition (Gonzalez, 2018). Food security may be approached from the supply side (i.e. food availability) or the demand side (i.e. access to food) (Xi and

Long, 2016). Food security is affected by changes in food consumption and intermediate variables (such as food prices and food availability).

First-generation biofuels may pose a threat to food security, depending on the global output of grains (Xi and Long, 2016). Furthermore, the rise of biofuels has been accompanied by financial speculation in agricultural commodity markets, resulting in increased food prices and decreased food security (Gonzalez, 2018). Second and (particularly) third generation-biofuels do not require agricultural land for their production, so they are not involved in the food vs fuel debate (Xi and Long, 2016).

Some scholars believe that the food versus fuel problem has been exaggerated (Xi and Long, 2016). For first-generation biofuels, double crops grown between growing seasons of food crops as well as mixed crop systems can produce biofuels without decreasing food production. Furthermore, some biofuel feedstocks may be used as both food and fuel, occupying a unique location at the intersection of energy, climate, and food law and policy (Gonzalez, 2018).

If policy support for (transportation) biofuels continues, algae as a feedstock can alleviate some of the pressure that conventional biofuels exert on food security (Doshi et al., 2016). Like second-generation biofuels, algae biomass does not have a direct opportunity cost for food supply. The change in food price volatility caused by algal biofuels should be equal to zero (Efroymson et al., 2017). Since agricultural land is not used for algal biofuels, the prices of algae and algal fuel should not interact with food price volatility.

Favorable effects on food security are mentioned, but a formal measurement is lacking (Efroymson et al., 2017). It has been suggested that algal biofuels could improve food security if defatted, high-protein residual algal biomass is used as a replacement for corn and soybean meals in swine and poultry diets. In addition, algae can add to the food supply by providing supplemental feed for aquaculture and feedstock (Rösch and Maga, 2012).

Yet, competition between food crops and algae for fertilizer could also affect food security (Efroymson et al., 2017). In addition, food volatility could be affected if algal biofuels are grown on pastureland, thus reducing meat production. Any hypothesized association between algal biofuels and food price volatility will only be confirmed when algal biofuels are in large-scale commercialization.

5.2.4. Transportation security

Biofuels interact predominantly with transportation security since they are liquid energy sources that may replace gasoline and diesel. Based on the global transport energy demand of 2016, Correa et al. (2021) estimated that around one million square kilometers of algal production would be needed to meet 30% of the transport energy demand in 185 countries. To meet this target by 2050, it was estimated that the algal production area would have to increase by 57%. This would require a small percentage of the land of most countries except a few very small countries with high energy demand (such as Luxembourg, Gibraltar, Bahrain, Hong Kong, Singapore and Macao). Future relative increases in algal production areas would be the highest for developing economies (like India, China, as well as countries in Africa and the Americas).

In 75% of the countries, algal production would require less than 1.5% and 2.5% of the country area to meet the transport energy demands of 2015 and 2050 respectively (Correa et al., 2021). Considering that electricity is likely to play a major role in the transport sector in the future, reducing targets in algal biofuel production would help limit conflict with agriculture and biodiversity especially in temperate countries.

Aviation has special needs with respect to energy security, such as developing locally based supply chains in every continent (Efroymson et al., 2017). As in the case of land transport, aviation requires liquid fuels, so other renewable energy options may be used. Research in the development of advanced biofuels has been carried out by the military as well, with the aim of ensuring future supplies of transport fuels that do not depend on fossil fuels (“Societal Benefits of Biofuels in Europe”, n.d.).

5.2.5. Energy security

Energy security is a concern historically associated with depleted fossil fuels (Chin et al., 2014) with the security of supply having been a particularly important concern (Doshi et al., 2016). If energy supply depends on imports, a country risks having its economy restricted by the fluctuations of the international energy market (Xi and Long, 2016) as well as geopolitical conflict. In the face of increasing energy demand in a geopolitically more uncertain world, countries are interested in increasing the share of renewable energy with domestic production so that they may replace energy sources that are unsustainable, reduce uncertainties associated with global energy markets, and create jobs in local communities (Correa et al., 2021).

Improving energy security may be considered a type of progress towards sustainability (Efroymson et al., 2017). Biofuels can help in this respect, increasing employment and helping achieve energy independence (Xi and Long, 2016). In fact, the high production efficiency of algal biofuels provides greater fuel security, justifying policy investments (as in the US) (Doshi et al., 2016).

The US is the world's largest producer and consumer of biofuels, accounting for over 40% of the global biofuel production (mainly corn-based ethanol) (Gonzalez, 2018). Nevertheless, the US may still need to import sugar-based ethanol from Brazil to meet its biofuel targets. Hawaii, a geographically isolated region of the US, depends on fossil fuels and is exposed to fuel price volatility and supply interruptions (Efroymson et al., 2017). These considerations have dictated Hawaii's focus on renewable energy, with a climate that is suitable for the production of algal biofuels.

The energy security of Europe is perhaps the most important driver for the production of biofuels ("Societal Benefits of Biofuels in Europe", n.d.). The EU uses 65% of its vegetable oil to produce biodiesel, imports significant biofuel feedstock from the Global South, and will likely need to increase imports to fulfil its mandate (Gonzalez, 2018). For developed countries, biofuels offer an opportunity for reduced dependence on oil from the Middle East, Russia or Venezuela (Sawyer, 2008). To this end, several nations aim to increase their mandatory biofuel blends, with Brazil setting it as high as 27% for bioethanol blends (Correa et al., 2021).

Replacing fossil fuels with biofuels has been promoted as a win-win means of mitigating climate change, improving energy security, fostering (local) economic growth, and addressing poverty (Gonzalez, 2018). Algal biofuels in particular help meet transport energy demands; offset the use of fossil fuels for the transport sector (together with electric mobility); promote job creation; lower environmental costs (compared to conventional biofuels); and improve national energy security (Correa et al., 2021). Yet, when biofuel production is subcontracted to other countries, national energy security and energy independence are exposed to additional risks.

Energy independence may interact with society, leading to a higher public opinion of renewable energy resources (Efroymson et al., 2017). Biofuels promise more energy independence and energy security (Doshi et al., 2016). The ease of access to the fuel is an advantage for developing communities (e.g. in Brazil and Africa) as it benefits employment (both in agricultural as well as research and development), productivity, commerce, and local trade.

If energy security was not a concern, the best areas for the production of algal biofuels would be barren and sparsely vegetated areas along the coasts of North and East Africa, the Middle East and western South America (Correa et al., 2021). Countries that have been targeted for land grabbing for biofuels (e.g. Somalia, Eritrea, Sudan, and the Democratic Republic of the Congo) are notorious for political instability, lack of democracy, and weak adherence to the rule of law (Gonzalez, 2018). China, India, Indonesia, and Japan have recognized the limitations of biofuels for energy security, placing more emphasis on their potential to contribute to rural development (Elder et al., 2018). Biofuels help diversify energy supply, however even the achievement of modest targets will require imports, with countries good for imports (other than Brazil) remaining unclear (Elder et al., 2018).

5.2.6. Other geopolitical considerations

Energy (including biofuels) is associated with geopolitical risks. Much of the remaining quantities of fossil fuels are concentrated in areas of continuing political instability such as the Middle East (“Societal Benefits of Biofuels in Europe”, n.d.). Energy installations affect national security and even renewable energy infrastructure could be targets for terrorist attacks (Vakulchuk et al., 2020) including biofuel installations whose strategic importance would be associated with their participation in the energy mix. Even an external supply of electricity could be used as an energy weapon.

Biofuel companies could have indirect positive impacts by improving the infrastructure (e.g. roads, electricity) in the regions they are active, which can improve logistics (by reducing the time it takes to collect food) and food accessibility (Xi and Long, 2016). Nevertheless, biofuel facilities could face resistance due to conflicts between national and local interests (Chin et al., 2014).

An estimated 70% of algal biofuel production will likely be concentrated in developed and developing economies such as the US, China, Russia, Germany, Canada, Italy, Japan, UK, India, Brazil, France, South Korea, Mexico, Italy, Indonesia, Iran, and Saudi Arabia (Correa et al., 2021). The US and the EU are the key drivers of biofuel markets and are expected to remain so, outsourcing production to the Global South in order to comply with their ambitious mandates (Gonzalez, 2018). Wood chips, grass, agricultural residues, and other low-value generic biomass are abundantly available in developed countries, so biofuel production could be moved nearer markets (Sawyer, 2008). Moreover, feedstock diversity is a strategic issue for national security (“Societal Benefits of Biofuels in Europe”, n.d.).

Countries that are located in low latitudes and have large dry areas that have been transformed by manmade activities and have low agricultural and biodiversity values, are ideal for algal biofuel production (Correa et al., 2021). For countries located in the temperate zone (including Canada, UK, France, Germany, Italy, Russia, and South Korea), biomass and lipid algal productivity is lower compared to tropical and subtropical regions because of fluctuating temperatures and solar irradiation. If algal biofuels were produced there, they would require larger land footprints and have larger production costs per area. Algal biofuel productivity is higher at lower latitudes, but tropical and subtropical countries include areas that are highly productive (although with young, relatively undeveloped soil horizons); may be developed with intensification and expansion of agriculture; and house the highest biodiversity values globally. Many of these countries are also developing economies, with high increases expected in transport energy demand and, therefore, likely conflicts between areas used for (conventional) biofuel production and agricultural areas or areas of high biodiversity.

It would make sense for algal biofuels production to be concentrated in countries with high energy consumption levels, but these typically do not have large tracts of dry land that have been transformed by human activity, have lower biodiversity value, are unsuitable for agriculture, and thus available for algal production (Correa et al., 2021). Promising areas for algal biofuel production are those that can support high lipid productivity and are characterized by low impact on agricultural lands and biodiversity.

The proportion of cropland used for biofuels varies by country and region (Xi and Long, 2016). High priority countries for algal biofuel production include developing economies in: North and East Africa; the Middle East; western South America; the Caribbean; and Oceania (Correa et al., 2021). Some high priority-countries for algal biofuel production are composed of islands (e.g. Haiti, Madagascar, and Papua New Guinea), but islands house more endemic species, so these countries are characterized by high extinction risk of (possibly endangered) native and endemic species. Both positive and negative impacts from the production of biofuels may be shifted to other countries directly by importing feedstocks and biofuels or indirectly by allowing domestic biofuel production to displace other domestically produced goods and services (Elder et al., 2018).

The development of (conventional) biofuels is likely to generate some geopolitical strife. Faced with global warming primarily caused by the consumption of fossil fuels as well as political insecurity in oil-producing countries, rich northern countries have been seeking alternative supplies of energy. Conventional biofuels have been considered a good alternative (Sawyer, 2008). The thing is, countries in the Global North lack the domestic capacity to fulfill their biofuel mandates, so they import from countries in the Global South, which in turn have expanded their biofuel production to meet such demand (Gonzalez, 2018). Indonesia and Malaysia export to the EU, while countries in Africa, Asia, and Latin America invest in biofuels at the expense of domestic food production.

Northern investors (representing investment banks and hedge and pension funds) speculate on cheap southern agricultural lands that expect to appreciate rapidly (Gonzalez, 2018). The South resists northern economic policies that are considered responsible for impoverishing the Global South and facilitating the appropriation of the planet's resources by the Global North. Environmental conflicts between the affluent Global North and the poor and middle-income nations of the Global South are an example of distributive injustice. North-South relations are also marred by procedural inequities, caused by the fact that decisions in international trade and financial institutions (like the World Bank, the International Monetary Fund, and the World Trade Organization) are driven by the perspectives and priorities of rich northern states and actors (like the US and the European Union).

For many developing countries, energy-intensive industries are important for economic growth (Xi and Long, 2016). The problem is that vulnerable states, impoverished people, racial and ethnic minorities, and indigenous populations possess the fewest resources to protect themselves against degradation (Gonzalez, 2018). The development of algal biofuels may help address these issues.

6. Discussion and conclusions

This chapter documented the state-of-the-art on the wider socioeconomic aspects of biofuels focusing on the third generation of biofuels produced from algae. The biofuels literature was reviewed, and its findings were organized into sections dealing with socioeconomic, public acceptance, environmental, ethical, policy and geopolitical aspects. Conventional biofuels require agricultural land; motivate deforestation; support the food vs fuel debate; and drive food prices upwards, problems largely avoided with algal biofuels. Public attitudes towards biofuels are largely driven by social norms which can catalyze emulation and motivate acceptance, although empirical research on the social acceptance of algal biofuels is lacking. The contribution of conventional biofuels to global warming remains questionable although their detrimental impacts on land, forests, biodiversity, and water quantity and quality have been largely established, but are much less of an issue for algal biofuels. Conventional biofuels are also associated with environmental injustice, also largely avoided by the production of algal biofuels. Finally, biofuels are associated with socioeconomic, ecological, food, transportation, energy and even national security, affecting favorably or unfavorably issues related to the Global North vs Global South debate.

As for the future, renewable energy is expected to dominate later in the 21st century (Saad et al., 2019). The future of algal biofuels relies on the establishment of cost-effective technologies for commercialization, social acceptance, and market diffusion. Experts believe that algae will be the source of one to 5% of global fuel consumption from 2021 to 2030, and potentially 10 to 25% of fuel consumption from 2031 to 2050 (Efroymson et al., 2017). A good question is this: can the future of sustainable mobility still include the internal combustion engine (Villarreal et al., 2020)? Perhaps so, with biofuels produced from algae, genetically engineered or not.

Will algal biofuels be a disruptive technology? Investopedia (Smith, 2020) defines a disruptive technology is *“an innovation that significantly alters the way consumers, industries, or businesses operate”*. The same source lists e-commerce, online news sites, ride-sharing apps, and GPS systems as current disruptive technologies and mentions that the automobile, electricity, and television were disruptive technologies in their time. Aluya (2015) argued that the success of a disruptive technology depends on the following factors: politics and leadership (of the related industry); minimization of social and ecological disruption (associated with the disruptive technology); decline in the supply of fossil fuels; increase in the global demand for energy; sustainability of the disruptive energy source; use of the disruptive technology to create an (assessable) opportunity; and investment risks. More specifically, Aluya argued that political considerations and established leadership styles could enhance or inhibit the introduction of disruptive technologies.

Culaba et al. (2020) referred to algal biofuels as a disruptive complementary technology that may contribute to sustainability. The debate on sustainable mobility and whether internal combustion engines should be banned altogether (and rely on electric cars powered by hydro, wind, and solar and having zero emissions), could affect the future of biofuels in general (Villarreal et al., 2020). Decentralized and small-scale production may be a more sustainable and secure way of solving the energy problem (Chin et al., 2014). In any case, many of the socioeconomic, environmental, and (geo)political factors reviewed in this chapter will play a role in determining whether biofuels disrupt the energy markets. Gomiero (2015) concluded that, should subsidy and food price trends continue, conventional *"biofuels could prove to be a major disruptive force, possibly benefiting producers but harming low-income consumers"*.

As to policy recommendations, recent Eurobarometer data (European Commission, 2019) has confirmed that European citizens consider climate change to be a serious problem; think that governments should get more energy from renewable sources; think that more public funding should be offered for transition to clean energy sources; and think that climate change mitigation measures adopted by businesses should make them more innovative and competitive. Yet, while it is easy to agree on issues like reducing the consumption of single use goods, and recycling, there is a diversity of attitudes towards the consequences arising from the policies intended to manage climate change and mitigate global warming. These have been underscored by a couple of research publications that wrote about *"energy tribes"*, but have received little attention over time. Thomson (1984) wrote of the existence of three such groups in society: business as usual, middle of the road, and radical change now. Caputo (2009) wrote of the existence of four such ways of thinking in society: egalitarianism, individualism, fatalism and hierarchy. Membership in different energy tribes reflects overlapping sets of rationality, different sets of beliefs, and different cultural values. People in different energy tribes place different bounds on what is credible/incredible, possible/impossible, sensible/foolish and rational/irrational. As a result, they have different attitudes and beliefs, and accept different solutions. Since policies can move forward only if embraced by a large majority for a long time, the existence of energy tribes means that only *“messy”* or *“clumsy”* policy solutions, combining the logic of different energy tribes, have a chance of working.

These considerations may be useful in designing effective policies for algal biofuels, which are a promising renewable fuel sources with many technological, environmental, and geopolitical benefits (compared with conventional biofuels) but remain relatively unknown among the general public. Although blindly pursuing alternative energy can be like *“robbing Peter to pay Paul”* (Xi and Long, 2016), fast-track algal biofuels could be an interim solution to replace transportation fuels in road and air transport, which are unlikely to be fueled by renewable electricity in the next couple of decades (Villarreal et al., 2020).

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