A Comprehensive Analysis on the Future of Algae Biofuels in China

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Abstract. As the biggest developing country on this planet, China is progressing in its economy, industry, and technology at an incredible speed, but along with this rapid development is the huge demand for energy. Conventional fossil fuels cover more than 70% of primary energy supply in China, while at the same time bringing environmental and economic issues. Renewable energy, such as bioenergy, might be the solution to resolve the energy crisis faced by China. China has a mild climate, plentiful water resources, and sufficient sunshine that are suitable for algae to grow, so algae biofuels might have a bright future to fulfill the need for energy in China in an ecologically friendly way. Based on existing studies, models, and data, this paper discusses the technological possibility and limitation, economic feasibility, and environmental benefits and concerns of developing algae biofuels in China. Lastly, the paper gives several future prospects to the system in order to make algae biofuels more practical to be a both commercialized and competitive energy source in China.

1. Introduction
Although China has a profound history of utilizing biomass and biofuels, recent national planning and policies did not pay much attention to the production amount of bio-energy, when comparing to other types of renewables such as hydropower and solar power. Undeniably, China is making progress in developing biomass and biofuels, such as transforming the major feedstocks of biofuels production from the first generation (grains such as wheat and maize) into the “so-called 1.5(second) generation” (cassava, sweet potato and sweet Sorghum)[1]. Nonetheless, issues related to food-energy competition as well as water and land usage will still remain, as long as the country is relying on these land-based feedstocks. On the other hand, China owns one of the longest coastlines on the planet, along with abundant freshwater and solar resources and a mild climate. These endow China the capacity to develop and commercialize the “third-generation biofuels”[2] based on algae, an ideal type of feedstock that has many potential economic and ecological advantages. However, China lacks a nation-focused comprehensive overview of algae biofuels since 2013, so this paper will analyze the development potential of algae biofuels in China from technological, economic, and environmental perspectives, to investigate the potential as well as pros and cons of algae biofuels in China, and to give prospects about its future.
2. Technology

2.1. Basic chemical, biological, and technical principles

In general, the process of transforming algal organisms into useful biofuels and by-products could be divided into Cultivation (planting and harvesting) and Refinery (treatment and conversion). Each step could be achieved in several different means and will result in different outcomes.

2.1.1. Cultivation.

Based on the raw materials and the design of the cultivation facilities, algae cultivation for the purpose of biofuels production could be classified into natural type and artificial type, and each type of cultivation has its own advantages and drawbacks.

Natural cultivation usually relies on natural water resources such as great rivers and lakes, and these natural resources are further constructed into small ponds or lakes for algae planting and harvesting [3], most typically the “raceway pond” design in Fig.1. These facilities are the easiest to initiate and maintain due to their relatively low capital and operating cost [3]. Besides, for marine macroalgae, a special kind of “coastal farm” could be built to plant and harvest the kelps in the shallow sea. However, problems raised by natural cultivation, such as conditions uncertainty, water and soil contamination, and uncontrollable CO2 emissions are still significant and should be taken into concern. The local topography also affects the possibility of implementing the raceway pond, which will be discussed later.

In contrast, artificial cultivation, or basically photobioreactors (PBRs), which cultivate algae in a closed, controllable environment, could avoid the problems mentioned above. There are many types of PBRs, shown in Fig.1, but generally they are all utilized by imputing needed materials-water, algae, CO2, and nutrients-as well as controlling the temperature, sunlight density, and pH level inside the reactors[4]. PBRs are safe, clean, flexible, efficient, and systematic, but at the same time expensive, energy-consuming, complicated, and thus needing precise design and control to reach the optimal condition of biomass cultivation.

![Photobioreactors (PBRs) used in growing microalgae: (a) raceway pond, (b) flat-plate type, (c) inclined tubular type and (d) horizontal/continuous type[5].](image)

2.1.2. Refinery.

Similar to other types of feedstocks, after cultivation algal biomass must undergo refinery processes in order to convert the lipids and carbohydrates in algae to bio-oils, bioethanol, and biogases. Bio-refinery also produces useful by-products such as agar and bio-fertilizer, for agricultural, medicine, food, and cosmetic use[6], but that is out of the discussion focus of this paper. Generally, biorefinery
approaches could be done by thermochemical, biological, chemical, or physical conversions, as shown in Fig. 2.

Figure. 2. Current biorefinery processes[6].

2.2. Technological Possibility and Limitation

As aforementioned, the technological barrier of commercializing the first and second generation of biofuels is that the feedstocks come from land-based plants, which require conventional farming skills and conditions. In contrast, the growth of algae does not require any arable land nor clean water, and algae could even grow in any environment with sufficient water, sunlight, and nutrients[2].

Considering this special characteristic of algae growth, potential algae biofuels factories should be set in areas undeveloped for urban construction, unsuitable for crops planting, and close to natural water resources (lakes, rivers, seas). Cultivating energy-aimed algae in these so-called “marginal lands”[7] will (1) avoid the energy-food nexus common in the first and second generation of biofuels feedstocks and (2) fully utilize the marginal areas, including natural scrubland, grassland, saline and alkaline land, etc.[7] However, the maldistribution of marginal land resources is severe within the country due to the province area, urbanization, and topography. In the near-term, The Northwest region (Gansu, Qinghai, Ningxia, and Xinjiang) has the highest potential of algae biofuels production, following by the Northeast region (Shandong, Heilongjiang, and Jilin). These are the regions with both sufficient marginal land (e.g. $3274.93 \times 10^3$ ha in Xinjiang and $276.73 \times 10^3$ ha in Shandong) and natural water resources (Songhua and Liaohe river in the Northeast, and Heihe, Tarim river in the Northwest, not shown on the graph).
Figure 3. Marginal land distribution in China (unit: 103 ha)[7,8].

Besides the North, Southwest China is also predicted to contribute greatly to the total energy-aimed algae production in China for more than 30% in the near future[7], considering the to be developed marginal land in Yunnan and Tibet and the sufficient solar energy because of the high altitude. However, technical limitations must also be deliberated before building algae biofuels factories. For one thing, the sloping topography in Yunnan and Tibet prohibits the application of raceway ponds (natural cultivation), and only photobioreactors (PBRs) are possible[5,7], but the high cost of PBRs, as well as transportation limitation, are also problematic[7]; similar setbacks also exist in the Northwest, especially Xinjiang, the region with most marginal land but at the same time one of the most underdeveloped provinces in China. In addition, macroalgae cultivation in those coastal areas in East China also conflicts with the civilization and urbanization of large coastal cities, such as Shanghai (Yangtze River Delta), Guangzhou and Shenzhen (Pearl River Delta). Further development and commercialization of algae biofuels in the marginal land of China will only be practical when these technological and geographical barriers are broken.

3. Economy

Although algae biofuels production seems technically possible in China, for broader use and commercialization, the technology also needs to be economically practical. This section will take microalgae biodiesel as an example to verify the economic feasibility of algae biofuels in China.

3.1. The Production Cost of Algae biofuels

The calculation method, data, and prediction of the production cost are derived from a recent study in 2019 led by the School of Civil Engineering and Mechanics of Huazhong University of Science and Technology in Wuhan, Hubei[9]. The researchers consider the overall cost of microalgae biodiesel from cultivation to extraction, including capital and operating costs as well as labor payment. The cost-related proportion and data are presented in Fig. 4 and Table 1.
Figure 4. Cost proportion of microalgae biodiesel production[9].

| Year  | 2019 | 2020 | 2021 | 2022 | 2023 |
|-------|------|------|------|------|------|
| Production cost (USD/kg) | 2.21 | 2.13 | 2.06 | 1.99 | 1.92 |

3.2 Cost Analysis, Calculation, and Comparison

According to the cost proportion of microalgae biodiesel production, most of the capital cost attributes to the spending on special construction (e.g. building PBRs on sloping areas), again emphasizing the importance of proper site selection to reduce the special construction cost. Besides, electricity consumption accounts for almost half of the daily operating costs, even more than the wages paid to the workers. This might because the greater applicability makes PBRs a more popular choice than natural cultivation but at the same time consumes more energy. Widely implementing the usage of natural cultivation could surely reduce the energy cost, but the tradeoff of feasibility, efficiency, and controllability should also be considered.

On the basis of the data in Table 1, it is easy to compute and compare the cost of microalgae biodiesel production with the cost of producing conventional types of fossil-based fuels. The sample calculation is listed below (note: although the price comparison could be done in USD/L, USD/kg, or USD/kWh, using the last unit will most intuitively reflect the cost of energy production):

- Take the lowest predicted cost from 2019-2023 of microalgae biodiesel,
  
  \[ C_m \text{ (cost per kg)} = 1.92 \text{ USD/kg} \]

- Take the average calorific value of biodiesel[10],

  \[ CV = 10.9 \text{ kWh/kg} \]
Ce (cost per kWh) = Cm / CV = 1.92 / 10.9 ≈ 0.176 USD/kWh

Based on the calculation, assuming that the combustion efficiency is the same, the cost of microalgae biodiesel production will still be relatively high at least in the next few years, twice or even three times the cost of producing conventional fossil fuels (0.0625 USD/kWh for gasoline, 0.0930 USD/kWh for ethanol, and 0.0528 USD/kWh for diesel, derived from the statistics of IEA in 2017 and converted from USD/L to USD/kWh, using the same method as the sample calculation[10,11]). It is obvious that unless there is a technology breakthrough that greatly reduces the cost of algae biofuels production, or a significant shortage of fossil fuels that increases their cost largely, microalgae biodiesel and other similar types of algae-based biofuels will not be economically attractive to the energy market, at least in the near future.

3.3. Additional Comment

Although it seems economically non-feasible for algae biofuels to be widely accepted by the energy market, it is worth mentioning that the economic analysis of algae biofuels should not be limited in the narrow sense. The development and commercialization of algae biofuels could actually bring up other social and economic benefits. For example, a study in 2015 simulated the potential growth in the local economy and employment rate-on account of the new job created and the additional consumption by the workers-brought by the commercialization of algae biofuels in China[12]. The researchers include this effect in the form of “multipliers” when analyzing the economic and employment impact.

![Figure 5. The economic and employment impact multipliers of the algae-derived biodiesel commercialization in China[12].](image)

According to Fig. 5, the commercialization of algae biofuels will directly, indirectly, or inducedly promote the local economy, especially in those underdeveloped provinces such as Yunnan, as aforementioned in section 1.2 one of the regions with the most potential of algae biofuels development. The cultivation of macroalgae as part of the “coastal farm” could also contribute to the development of local fishery and aquaculture in small coastal cities in East China, for example in Fujian or Guangdong. As a result, pure production cost comparison should not be the only parameter when thinking over the economic feasibility of algae biofuels. Indirect economic advantages from the investment of algae biofuels should also be taken into consideration when Chinese government designs and implements its policies.

4. Environment and Ecology

As a type of bioenergy, one of the most popular renewable and clean energy sources, algae biofuels will surely do some good to the environment in China. However, the wide implementation of algae biofuels production might accompany several environmental problems and concerns that needed to be prevented or solved. It will be crucial for the policymakers in China to do proper cost-and-benefit marginal analysis and to find a balance between exploiting and protecting the environment and ecology during the development of algae biofuels.
4.1. Environmental Benefits
The most typical advantage owned by algae biofuels is their contribution to the reduction of GHG (Green House Gases) emission in the energy system. Although the combustion of algal biomass products, such as biodiesels and biogases, still emit carbon dioxide, the special characteristic of intaking CO2 by photosynthesis during the growth cycle of algae makes algae biofuels a “carbon neutral” type of fuels. According to a 2011 model, 45% of carbon emission will be cut if algae biodiesel replaces the role of conventional fossil diesel[13]. Extensive use of algae biofuels might be a solution to mitigate climate change and global warming, one of the most gordian issues faced by human beings. The same model also suggests a reduction of 55% life-cycle energy consumption[13], due to the simplicity of cultivating the feedstocks and high efficiency during the dewatering and centrifugation of algae in the refinery process. Algae biofuels production also has its ecological benefits. The abundant amount of food (microalgae as phytoplankton) and habitats (macroalgae as the “marine forest”) will be provided to the local ecosystem if the natural cultivation method is utilized, indirectly improving the biodiversity and the protection of rare aquatic animals in China. By the way, kelp could also be a back-up food source for human beings for emergency use[14]. Moreover, the strong vitality and adaptability of some types of algae allow them to grow in so-called brackish water (seawater and industrial sewage). This will enable China to (1) reduce the water consumption from 200-2000 gallons of freshwater per gallon of biofuel from algae to about 8-200 gallons[14] and (2) relieve stress in wastewater and polluted air treatment as algae uptakes chemicals such as phosphorus, potassium, and heavy metals as nutrients when they grow.

4.2. Environmental Concerns
Although developing algae biofuels production has its own benefits, there are still problems and concerns related to this technology from environmental and ecological perspectives. Cultivating algae in natural environments such as lakes or shallow seas might lead to competition in the local ecosystem and cause damages. One typical example is the “algal bloom”: when water eutrophication happens, algae grow at an incredible speed, cutting off the sunlight and taking away oxygen through cellular respiration, and thus resulting in a large number of deaths of fish. Using the raceway ponds or PBRs that cultivate algal feedstocks in an isolated environment might be a solution to this issue, but will bring up other concerns. An ecological system with only algae is weak in biodiversity and self-defense function, and thus may attract invading species as well as predators, severely reducing the overall amount of output[14]. The sewage from the raceway ponds and PBRs is also a potential issue, as they could carry disease-causing pathogens and toxic chemicals such as heavy metals, which will bring huge problems to the public health in China when they enter the source of drinking and using water in the local community. What’s more, as aforementioned, algae biofuels are not economically competitive in the energy market, partly because of the relatively low productivity. Genetic modification (GM) could be utilized to multiply the production amount of algal biomass[3], but nowadays GM is such a controversial topic that its overall advantages and potential problems have not been fully discovered. If GM itself actually has problems, then cultivating genetically modified algae may be a threat to the local ecosystem by changing the genotypes and phenotypes of local aquatic plants or affecting the health of animals or even humans, which is a problem that now has no definite answer, but at the same time must be considered when Chinese government makes related policies.

5. Conclusion
Algae biofuels are a technologically possible, environmentally friendly, but economically non-competitive source of energy in China. Two ways of cultivation could be implemented: natural and artificial, followed by several refinery processes to convert algal biomass into useful biofuels and byproducts. From an economic perspective, algae biofuels are still much more expensive than fossil-based fuels but at the same time show considerable benefits to the local economy, so pure cost analysis should not be the only parameter. Finally, algae biofuels derive from a clean and renewable method, thus offering many environmental and ecological advantages, but still hold problems and concerns.
6. Prediction and Suggestion
Due to its economic impracticability, algae biofuels are not recognized to be a highly developed and commercialized source of bioenergy in China, at least in the next few years, while the environmental superiority and technological maturity are still considerable. Future research and development must focus on the site selection of algae biofuels production factories based on natural resources, the type of cultivation depending on topography, and special attention to genetic modification technology. One possible policy that could be made by the Chinese government, proposed by environmental engineer Andre Dupont, is an integrated system of wastewater & air pollution treatment and algae PBRs[14], fully utilizing the function of algae to clarify water and air, and producing algae biofuels. On the economic side, a technological breakthrough is required to bring down the cost of producing algae biofuels, but policymakers could also consider the development of algae biofuels production as a means to promote the local economy and provide job opportunities, especially in Tibet, Yunnan, and some small coastal cities in Guangdong and Fujian.

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