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The Potential of Algae Biofuel as a Renewable and Sustainable Bioresource †

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Abstract: Algae are promising sources of biofuel. Microalgae's ability to grow quickly with photosynthesis, carbon dioxide, and nutrients makes them ideal biofuel sources that do not compete for resources with food crops like corn. Algae cultivation on non-arable land allows it to produce biofuel while not competing with them for resources. Algae biofuel has many advantages over fossil fuels, including reduced greenhouse gas (GHG) emissions and carbon emissions. There are various methods for turning algal feedstock or biomass into advanced biofuels. Algae biofuels have become widely used as fossil fuel replacements; however, several challenges must still be overcome, such as high production costs, the need for extensive growing systems, harvesting techniques that enable efficient harvesting/extraction techniques, as well as efficient harvesting/extraction technologies.

Keywords: algae; biofuel; sustainable; renewable; bioresource

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1. Introduction

Recent years have witnessed global energy consumption steadily increase as a result of rapid urbanization and industrial development [1]. Conventional fossil fuels such as oil, coal, and natural gas still represent the primary energy supply [2]. Renewable and sustainable sources such as wind, solar, tidal hydropower, and biomass must be applied to meet the increasing energy demands. Algae species boast over 30,000 varieties that reproduce rapidly, making them one of the most diverse groups among plants [3]. Microalgae are capable of rapidly growing through photosynthesis, carbon dioxide, and nutrients and also of producing significant oil production that can be extracted by disrupting their cell structure and producing biofuels (Biodiesel, Bioethanol, Biohydrogen, Bio-oil, and Biohydrogen). With various conversion processes such as Transesterification Fermentation Pyrolysis and Anaerobic Digestion [4,5], algal feedstock could easily be transformed into algae-based biofuels [4]. The algae can withstand almost all environments and temperatures, including extreme cold and scorching heat. They can eliminate CO_2 from industrial chimney gases by bio-fixation and, after oil extraction, produce electricity or heat energy as well as biofertilizer, animal feed, healthcare products, and food products.

2. Overview of Algae

A wide variety of algae exist in different sizes and forms, including single-celled microalgae and the largest multicellular seaweeds. Algae produce organic compounds through photosynthesis. Algae are highly efficient biofuel sources due to their ability to convert solar energy directly into biomass [5].

2.1. Classification of Algae

Algae can be classified according to various characteristics such as size, cell type, habitat, energy source, pigment color, and motion. The classification of algae is discussed further below and illustrated in Figure 1.

Size: Depending on the size of an organism, the term "alga", can refer to either a single-cell organism or a multicellular seaweed. Diatoms are unicellular organisms that can grow to a maximum of (2–200 µm). Some species of brown algae can grow as long as several meters.

- Cell Types: Algae can be divided into unicellular and multicellular groups according to their cellular structures, with some species featuring only one cell while others like seaweed have multiple.
- Habitat: Algae can be classified into four distinct habitats based on their environment: freshwater, marine, brackish, or moist terrestrial. Although most green algae prefer freshwater environments for growth, some species also thrive in brackish marine waters due to the brackish conditions where they originate from. In freshwater environments, some green filaments float freely while others become attached to rocks or roots and flow with fast currents through still waters or swift currents.
- Energy Sources: Algae can obtain their energy either through photosynthesis, chemosynthesis, or some combination thereof.
- Pigment color: Algae can be classified by their pigment color as either green, red, brown, or blue-green depending on which wavelengths of light they absorb to ensure survival in various environments.
- Movement: Algae can be divided into non-motile and motile classes depending on their movement through the water. Some green development species can simply drift along rivers while others use flagella or plans to propel themselves through it—or both! There are various orders for how well they interact with their environment, which has different needs for movement.

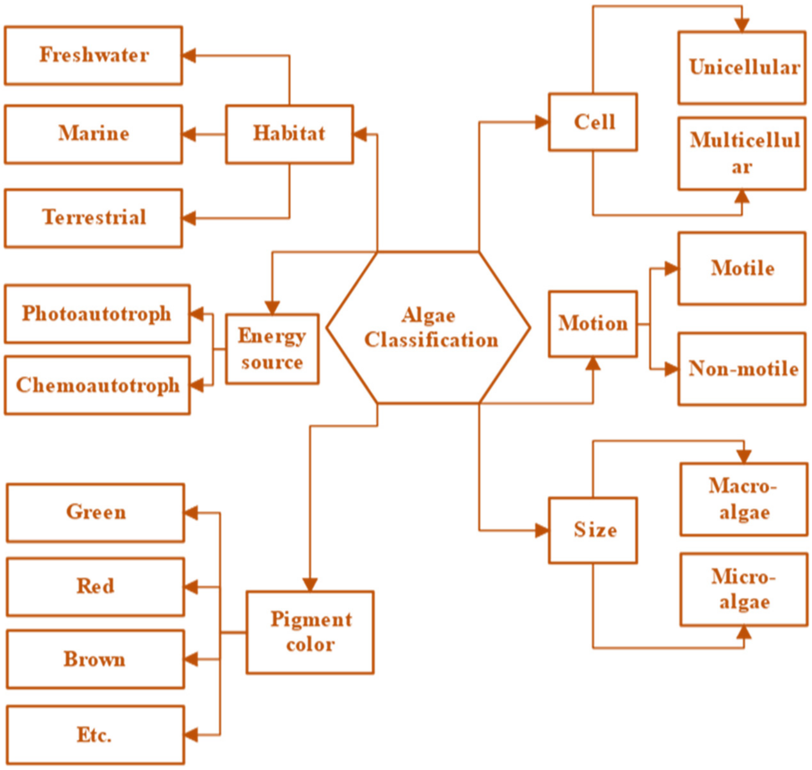

Figure 1. Classification of algae.

2.2. Sustainable Development of Algae

Sustainably developing algae means using this natural resource in a way that minimizes greenhouse gas emissions while decreasing our dependence on non-renewable resources [6]. Furthermore, sustainable development means minimizing negative environmental impacts while optimizing economic and social benefits—Table 1 details these applications and benefits of algae in sustainable development in various fields.

Table 1. Algae's contributions to sustainable development in a variety of contexts [6–14].

Areas	Application	Benefits
Energy Production	Power generation	- Algae-powered microbial fuel cells produce electricity - Algae biogas used to generate electricity
Environmental Remediation	Carbon sequestration	- Algae improve water quality, ecological health, and biodiversity - Algae are used as carbon reservoirs by stores.
Food and Agriculture	Nutrient Supplement	- Nutritional vitamins, minerals, and omega-3 fatty acids are found in algae
Sustainable Materials	Bioplastics	- Algae-based bioplastic - Algae-based polymers help reduce plastic use and waste
Waste Management	Wastewater treatment	- Algae extract nutrients and toxins from wastewater

2.3. Types of Algae Biofuels

Different biomass from different sources like forests, farms, and aquatic environments has been considered feedstock for the production of various biofuels such as biodiesel, bioethanol, biogas, bio-oil, and biohydrogen. Algae are an economical and eco-friendly choice when it comes to producing biodiesel; numerous techniques exist that transform it into algae-based fuels. Table 2 details their production process.

Table 2. Production process of algae biofuel [8,15–18].

Types of Algae Biofuels	Production Process
Biodiesel	Transesterification
Bioethanol	Fermentation
Biohydrogen	Fermentation
Bio-oil	Pyrolysis
Biogas	Anaerobic digestion

2.4. Advantages of Algae Biofuels

Algae biofuel offers several advantages over traditional fossil fuels and other biofuels. Table 3 lists these advantages of algae biofuel with descriptions.

Table 3. Advantages of Algae Biofuels [19,20].

Advantage	Description
Carbon neutral	Conversely, algae absorb CO_2 during growth which balances out any CO_2 released during combustion.
High productivity	Algae are an attractive biofuel crop due to its fast growth rate and high biomass output per unit area.
No competition with food crops	Algae are not a competition to food crops.
Potential for sustainable production	Algae can be grown safely and sustainably within an enclosed system (photobioreactor), eliminating contamination risk while simultaneously supporting sustainable production.
Versatility	Algae can produce biodiesel, bioethanol, biohydrogen, and bio-oil as by-products from their fermentation. Biogas production also depends on algae for power.
Waste reduction	Algae can be grown using wastewater or carbon dioxide emissions from industrial processes, reducing pollution and waste while decreasing pollution levels.

2.5. Indian Scenario of Algal Biofuel

India currently ranks fifth globally, using 4.1% of global energy production. By 2025, however, it is expected to surpass both China and the US to become the third-biggest energy user worldwide. India boasts the world's highest urban electrification rate (93.1%), as well as the world's largest rural population rural electrification schemes, which are implemented at various times across rural regions; however, the limited electricity-generating capacity in India makes these plans hard to implement [21]. India has shown increasing interest in algae production for various purposes and is taking steps to advance it through research, development, and commercialization [22]. Table 4 depicts India's recent progress and program related to algal biofuel.

Table 4. The Indian scenario of algal biofuel in recent years [23–25].

Year	Research/Program
2010	The Department of Biotechnology (DBT) initiated its "National Program on Microalgal Technologies" to advance the development and utilization of microalgae in India.
2012	The Indian government announced plans to produce biofuel from algae—to produce 20,000 tons of algal biofuel per year by 2017.
2013	The Indian Institute of Technology Madras IITM established a pilot-scale facility for cultivating microalgae for biofuel production.
2016	The Department of Biotechnology (DBT) established the University of Madras' "Centre of Excellence for Algae Research" to further promote algae research and technology development.
2017	The Council of Scientific and Industrial Research CSIR launches a project to develop cost-effective technology for producing biofuel from algae.
2020	The DBT and International Energy Agency's (IEA) "Bioenergy Task 39" recently issued a joint report on India's potential algal biofuel market, calling for further research and development to overcome technical and economic obstacles to algal biofuel development.

2.6. Challenges of Algae Biofuels

Algae biofuels have long been seen as a potential replacement for traditional fossil fuels in our energy needs, producing biofuels from algal biomass with several advantages over first- and second-generation feedstocks. Unfortunately, algae biofuel production remains underdeveloped on a large scale; therefore, revisits will need to take place to address any technology-related issues. Table 5 offers details of all of these issues with algae biofuel production.

Table 5. Algae Biofuel Challenges [26,27].

Challenges	Description
Contamination	Growing algae can be challenging in terms of avoiding contamination.
High production cost	Algal biofuels have become more expensive to produce in comparison with fossil fuels.
Land use	Massive cultivation of algae would require considerable space, which may conflict with other activities like farming or protecting wildlife habitats.
Scalability	One of the greatest challenges associated with algae farming is scaling.
Temperature and light	Air, water, and light conditions may alter algae growth and yield due to changes in environmental conditions.
Water quality	Maintaining water quality in an industrial-scale algae farm poses a significant technological challenge.

3. Conclusions

Microalgae have one of the fastest growth rates among photosynthetic organisms and can be grown on non-arable soil using wastewater as their nutrient source, offering exciting prospects for biofuel production from them. Algae-based fuels are considered one of the most cost-effective, renewable, sustainable, environmentally friendly solutions to climate change and food security, potentially meeting long-term global fuel demands by meeting energy demand from microalgae cultivation approaches as well as efficient low-cost harvesting methodologies. Nevertheless, more research needs to take place for microalgae to produce more biofuel than currently possible due to cultivation approaches as well as the lack of effective low-cost harvesting mechanisms from this organism.

Supplementary Materials: The presentation materials can be downloaded at: https://www.mdpi.com/article/10.3390/ECP2023-14716/s1.

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