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RESEARCH ARTICLE

"THERMAL CONVERSION OF ALGAE INTO BIOENERGY: A COMPREHENSIVE REVIEW OF PROCESSES AND PROSPECTS"

M.Fathima[1], S. Ayesha Sithika[2], B. Sowmiya[2] and V. Sanju Shree[2]

1. Assistant Professor, Vivekanandha College Of Engineering for Women, Department of Biotechnology, Namakkal, Tamilnadu- 637205.
2. Student, Vivekanandha College Of Engineering for Women, Department of Biotechnology, Namakkal, Tamilnadu- 637205.

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Abstract

The growing demand for renewable energy sources has prompted the investigation of algae as a possible feedstock for bioenergy production. This study looks into the thermochemical conversion of algal biomass into bioenergy using a variety of techniques, including pyrolysis, gasification, and hydrothermal liquefaction. Temperature, residence time, and catalysts were investigated for their effects on bio-oil yield and composition, as well as syngas and biochar.

Introduction:-

Algae thrive in water, particularly in wet environments like lakes and ponds. Algae plants use sunlight and carbon dioxide (CO_2) to produce biomass[1]. There were two classes of algae: microalgae and macroalgae. Microalgae Interest in Sustainable power sources based on Algal biofuel source conversion has developed Because of its adaptability for biofuel generation, such as biogas/biomethane, biodiesel, biohydrogen, bioethanol, and biobutanol, depending on the chosen technique[2]. The unique composition of algae allows them to be processed into biodiesel via transesterification, biogas via anaerobic digestion bioethanol via fermentation, and bioelectricity through cultivation in microbial fuel cells (MFC). It was reported that a biogas yield of 740 ml/g volatile solid was obtained using treated algae waste and co-digestion of corn husk[3]. Biodiesel from microalgae was an appealing option to valorize the micro-algal biomass, however, the solvents necessary for the extraction process add to greenhouse gas emissions [4].The use of fossil fuels has considerably led to air, water, and soil pollution, which has a detrimental impact on public health; an energy crisis driven by the irreversible depletion of global fossil-fuel reserves; and accelerated climate change[5].Waste management, bioenergy, biotechnology, forestry, fisheries, and agriculture were major industries that drive the bioeconomy[6]. Promoting clean and sustainable energy was critical for ensuring energy

Corresponding Author:- M.Fathima
Address:- Assistant Professor, Vivekanandha College Of Engineering for Women, Department of Biotechnology, Namakkal, Tamilnadu- 637205.

security while also protecting the environment. In recent years, biomass has been identified as a promising renewable energy source to address these difficulties, with algae gaining popularity due to its rapid growth rate, high photo-synthesis efficiency, and global distribution. When contemplating algae refining strategies, the primary option was to produce biofuels like bioethanol and biohydrogen[7]. As energy and environmental issues become more serious, particularly excessive CO_2 emissions, governments around the world have agreed to create and use clean and renewable energy resources.[8]There were three basic types of fossil fuels found in nature in their raw form: oil, gas, and coal. Because these were non-renewable resources that cannot be replenished indefinitely, science and technology were emphasizing sustainable development. Because the demand for petroleum use is substantially bigger and it's a non-renewable energy resource, recently the research emphasis has switched to the extraction of biofuel from biobased sources[9]. Specific areas of concern include production costs, energy consumption, product losses,and overall performance of microalgal biorefinery processes, as well as their environmental implications[10].

2.OVERVIEW OF THERMOCHEMICAL CONVERSION TECHNOLOGIES:-

Conventional fuel sources Oil is heavily used and has many large-scale applications in our daily lives. Coal and gas have approximately identical rates of misuse. It demonstrates the various applications of fossil fuels and the pace of consumption. The above graphic depicts how important biofuel will be in the future. Since it is described as a sustainable, renewable, and environmentally beneficial fuel. The Indian government has recently taken a major advancement toward sustainable development as part of the recent G20 summit held in New Delhi, India, to develop a sustainable economy through technological development, resulting in increased biofuel consumption and overseen by a newly formed body known as the Global Biofuel Alliance (GBA). In addition, the Indian government's Ministry of Heavy Metals has set a goal of incorporating 20% ethanol into gasoline by 2025, which might be a very promising method for sustainably establishing a sustainable economy. The above graphical plot illustratesthe percentage consumption, which represents India's progressive Innovation in the applicability of biofuel [11].

3.FEEDSTOCK CHARACTERISTICS AND PREPARATION:-

Global reserves of fossil fuels were limited. The burning of fossil fuels releases large amounts of greenhouse gases, which biofuels like ethanol and biodiesel could help mitigate. In 2015, global ethanol production reached 25,600 million gallons, indicating its potential as a biofuel. Nations such as the United States, Brazil, China, and the European Union aim to blend ethanol with gasoline. Various methods of biofuel production, including biochemical and thermochemical processes, along with biorefinery outputs, were explored regarding biomass. Biomass resources are cultivated in diverse settings, such as agriculture, industry, and residential areas, and can be transformed into energy through thermal or biochemical processes like fermentation, gasification, pyrolysis, combustion, and digestion. Specific conversion methods can be used either separately or together to produce bioenergy from different kinds of biomass, enabling the effective utilization of biomass resources to meet local energy economic objectives[12].

4.PYROLYSIS OF ALGAL BIOMASS:-

Pyrolysis refers to the method of converting solid biomass feedstock into three primary products: biochar, bio-oil, and gas, through high-temperature processes conducted without air. Recently, the production of liquid gasoline via pyrolysis has become increasingly popular. This technique was considered an eco-friendlier option compared to combustion, which transforms biomass into heat while releasing CO_2 and other pollutants. Pyrolysis functions as a thermal decomposition technique whereby the feedstock was heated to between 350 °C and 550 °C in an inert environment, followed by an increase in temperature to approximately 700 °C and 800 °C. The breakdown of long molecular chains comprising biomass leads to the formation of biochar, bio-oil, and syngas. The composition of the biomass feedstock significantly determines the yield of each product (solid, liquid, or gas) produced during pyrolysis. One of the byproducts of pyrolysis was biochar, which can be utilized as raw feedstock or burned for energy. Bio-oil consists of the condensed vapors generated throughout the pyrolysis process. Syngas is produced from non-condensable gases such as CO2, CO, and CH. Besides the feedstock's composition, the yield of each product and its formation mechanism were greatly affected by operational factors (pressure, temperature, residence time, type and flow rate of inert gas, and reactor type) that influence the pyrolysis rate. The amount of biogas generated is around 136 EJ, and this can be used for transportation, heating, and electricity generation.Since 2016, the production of biogas in Malaysia has been largely influenced by the palm oil sector. Reports indicate that biogas production in 2018 averted 464,000 tons of CO_2 emissions, contributing to 226 GWh of the country's renewable energy. Various types of waste can be used to produce biogas, including biohydrogen and biomethane. An energy biorefinery approach is utilized for the production of algae-based biogas. Gasification of algae is a method that transforms lignocellulosic biomass into gaseous substances with elevated levels of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2)[13].

4.1 Coal and Algae Blends:-

As coal was Malaysia's principal source of electricity, the increasing tendency of coal-fired power plants in recent years, compared to 20 years earlier, has prompted SahabatAlam Malaysia to encourage the government to restructure the country's energy sector[14]. The goal was to transition primary energy sources to renewables rather than relying on GHG-emitting sources[15]. Biomass blends such as sawdust, rice straw, and woodchips, as well as biomass particles, were evaluated for performance, synergistic effects between coal and biomass, kinetic studies, and other factors[16].

4.2 Bio Ethanol:-

Bioethanol was a type of liquid biofuel made from a variety of feedstocks, including wheat, corn, sugarcane bagasse, microalgae, and others, and is now utilized as a fuel additive in the petroleum industry. The addition of bioethanol to gasoline reduces greenhouse gas emissions to the environment and slows the depletion of fossil fuels[17].To meet global demand, the choice of feedstock was critical for large-scale production. The initial and subsequent generations of bioethanol feedstock Require cultivable land for growth, resulting in food competition and water use for energy crops rather than food crops, all of which are negative elements in bioethanol production. Microalgae were possible feedstock for renewable energy due to their quick growth rate, which allows them to complete a harvest cycle in 1-10 days without the need for arable land cultivation[18].Because of their flexibility and ease of growth, microalgae can be found in any stagnant waterbody or Polluted stream and can be harvested for further use, such as biofuel production[19].

4.3 Bio Diesel:-

Biodiesel use worldwide has reached 9.3 billion gallons, with the United States leading the way with 2.1 billion gallons in 2016 (U.S. Energy Information Administration, 2020). Biodiesel production was estimated to achieve an annual output of 16.5 billion liters across the European Union, and an average yearly production of 14 billion liters from the United States between 2023 and 2025. Despite the expected trend in biodiesel production, biodiesel demand is determined by the amount of biodiesel consumed in the countries, which was partly dependent on biofuel regulations that will be amended in all countries shortly. Biodiesel was mostly manufactured from animal fats, vegetable oils, waste cooking oils, algal oil, etc., which undergo transesterification to yield the finished product. Because food rivalry was an issue for biodiesel made from edible oil, non-edible vegetable oils such as Jatropha and non-edible algae were the best options for biodiesel feedstock. One disadvantage of animal fat was that they require a higher processing cost than vegetable oil, which produces problems during the production process. This was because animal fats are solid at normal temperatures[20].

4.4 Bio Gas:-
Biogas production worldwide has increased from 2000 to 2018, with 59.3 billion produced in 2018 (World Bioenergy Association, 2020). The amount of biogas generated was around 136 EJ, and this can be used for transportation, heating, and electricity generation. Since 2016, the production of biogas in Malaysia has been largely influenced by the palm oil sector. Reports indicate that biogas production in 2018 averted 464,000 tons of CO_2 emissions, contributing to 226 GWh of the country's renewable energy[21]. Various types of waste can be used to produce biogas, including biohydrogen and biomethane. An energy biorefinery approach is utilized for the production of algae-based biogas.

5. GASIFICATION OF ALGAE:-
Gasification of algae was a method that transforms lignocellulosic biomass into gaseous substances with elevated levels of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2)[22].This transition can occur at high temperatures (usually above 700 °C in finely controlled air, oxygen, and/or steam settings. The resulting gas combination (gaseous products) transformation was known as synthesis gas (syngas) or producer gas, and it can be utilized as a fuel due to its combustible constituents, such as H_2 and CO. Notably, gasification of lignocellulosic biomass has the potential to significantly increase the exergy efficiency of a Combined Heat and Power (CHP) System. IS and CV co-gasification can be separated into drying, pyrolysis, oxidation, reduction, and reforming depending on reaction sequences and temperatures. During the initial co-gasification of IS and CV, the feedstock was dried at a low temperature, resulting in moisture loss. As the surface temperature of feedstock increased, pyrolysis (R_2) occurred, producing char, tars, and pyrolytic gases such as H_2, CO, CO_2, CH_4, and other hydrocarbons. The volatiles and char products react with the injected gasifying agent producing heat to maintain endothermic gasification events [23].

6. HYDROTHERMAL LIQUEFACTION OF ALGAE:-
Biodiesel was the process of collecting lipids from algae and converting them into methyl ester through the transesterification process. The primary components of an algal cellswere lipids, carbohydrates, and proteins. Algal biomass grows 5 to 10 Significantly quicker than other usual feedstocks, hence Most of the biomass remains unutilized after lipid extraction, even partial lipid. Thus, thermochemical conversion is a promising alternative for entire feedstock conversion and biofuel production. Furthermore, several platform chemicals were generated through the thermochemical conversion of biomass[24].

6.1 Application of Conversion Process in Algae-Based Biofuel Production
Table 1

Algal organisms	Conversion process	Product	References
Saccharinalatissima	Hydrothermal gasification	Hydrogen gas	Onwudili et al. (2013)
Enteromorphaprolifera	Hydrothermal liquefaction	Bio Oil	Zhou et al. (2010)
Phaeodactylumtricornutum	Hydrothermal gasification	Methane	Haiduc et al. (2023)
Scenedesmusdimorphus	Pyrolysis	Bio Oil	Bordoloi et al. (2024)
Rhizoclonium sp.	Transesterification	Biodiesel	Saengsawang et al. (2020)
Chlorellaand Phormidium sp.	Hydropyrolysis and anaerobic digestion	Biomethane	Choudhary et al. (2020)
Scenedesmusrubescens	Transesterification	Biodiesel	Tsavatopoulou et al. (2020)
Chlorella vulgaris	Catalytic cracking Anaerobic	Biokerosene	Pujan et al. (2023)
Scenedesmusdimorphus	Anaerobic digestion	Biogas	Mediboyina et al. (2020)
Chlamydomonas sp.	Fermentation	Bioethanol	Kim et al. (2020)

7. TECHNO-ECONOMIC ANALYSIS AND CHALLENGES:-

7.1 Integrated withSome Alternative Renewable Energy Solutions

Thermochemical biomass conversion-based integrated renewable energy system that includes electricity generation and biochar production from lignocellulosic biomass using various thermochemical processes and renewable energy technologies to achieve negative greenhouse gas emissions. The planned configuration of the integrated system for simultaneous power generation and biocharmanufacturing [25].

7.2 Integrated with Solar Thermal Energy:-

There are few studies in the literature that combine pyrolysis of lignocellulosic biomass with solar thermal energy. For example, [26] suggested a renewable energy system that combines lignocellulosic biomass pyrolysis and solar thermal energy. Finally, the overall system's annual pollutant degradation energy was estimated to be 280 trillion seJ. As a result, despite its low environmental effect, the integrated system was deemed unsuitable for usage with local renewable resources. Similarly, Perkins studied two integrated renewable energy systems: solar PV/bio-oil combustion and solar PV/battery storage. The bio-oil used in the combustion was derived from lignocellulosic biomass by pyrolysis. Based on comparable assumptions, the levelized cost of electricity for the solar PV/bio-oil combustion and solar PV/battery storage systems was calculated to be 116 AUD MWh^{-1} and 170 AUD MWh^{-1}, respectively, for a daily energy production scale of 240 MWh. These costs demonstrated that the lignocellulosic biomass pyrolysis-based integrated system may be more economically viable than alternative renewable energy solutions [27].

8.Environmental Impacts on Stainability:-

With scientific advancement and industrial expansion, the rate of pollutant emissions has tended to increase exponentially. Several dangerous chemicals and other toxins are disposed of in water bodies and on land, causing serious health problems today. If eaten, some industrial effluents might cause leukemoid responses, hormone instability, birth malformation, and other health issues [28].

8.1 Air pollution:-

Numerous refineries and chemical process businesses discharge industrial gaseous effluents straight into the atmosphere, endangering human health and other living species. The releaseof effluents comprises various hazardous aromatic hydrocarbons, which immediately impair socioeconomic situations because they can cause carcinogenic and mutagenic effects if ingested. According to the radar graphic below, dust and constructionswere the primary sources of air pollution. Burning plastics and municipal rubbish also contribute significantly to the emission of harmful and hazardous air pollutants. Several industries and diesel-powered vehicles release quantifiable levels of air pollution, inflicting severe and detrimental effects on human health and, as a result, disrupting socioeconomic success[29].

8.2 Soil Pollution:-

Because of the low mass-volume ratio, slow rate of emulsion, and high viscosity forces, crude has the ability to deform soil enrichment by disturbing acid value, saline concentration, C-P ratio, and C-N ratio, thus reducing overall soil quality. The remaining crude can restrict soil nutrition, inhibiting soil enrichment, and fertility rate, and hampering contagion resistance[30].

8.3 Water Pollution:-

The petrochemical industry and other potential oil refineries emit toxic wastes consisting of convoluted structures in the form of gaseous and liquid phases, as well as a few harmful metallic compounds that can suppress immune responses in the human body by causing carcinogenic activities and ribonucleic acid alternation[31].

Conclusion:-

Biological CO_2 capture was a promising solution to reduce CO_2 emissions and remove surplus carbon from the environment. Cultivating microalgae and cyanobacteria on a large scale has environmental benefits and can produce a variety of useful goods, contributing to a more sustainable and circular bioeconomy. While microalgae and cyanobacteria have made tremendous progress in the bio-capture of CO_2, more study was needed to improve their efficiency. Biological CO_2 capture was a potential strategy for reducing CO_2 emissions and removing surplus carbon from the atmosphere. Large-scale cultivation of microalgae and cyanobacteria has environmental benefits since it allows for the production of a diverse portfolio of valued products, contributing to a more sustainable and circular bioeconomy.

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