GSC Advanced Research and Reviews
eISSN: 2582-4597 CODEN (USA): GARRC2
Cross Ref DOI: 10.30574/gscarr
Journal homepage: https://gsconlinepress.com/journals/gscarr/

(Research Article)

Check for updates

Biofuel: A sustainable and clean alternative to fossil fuel

Abubakar Musa Shuaibu [1,*], Usman Hassan Alhassan [2], Abubakar Muhd Shafi'I [1], Mohammed Sani Kolere [3], Ritu Sharma [1] and Ibrahim Abdurrashid [1]

[1] *Department of Chemistry, Faculty of Science and Technology, Mewar University Gangrar, Chittorgarh, Rajasthan, India.*
[2] *Faculty of Engineering, Department of Petrochemical Engineering, Mewar University Gangrar, Chittorgarh, Rajasthan, India.*
[3] *Department of Chemistry, Faculty of Science, Ahmadu Bello University, Zaria, Nigeria.*

GSC Advanced Research and Reviews, 2024, 21(02), 204–222

Publication history: Received 09 September 2024; revised on 02 November 2024; accepted on 04 November 2024

Article DOI: https://doi.org/10.30574/gscarr.2024.21.2.0382

Abstract

Increasing fuel consumption has threatened energy supply stability, raising significant environmental and economic concerns for many countries. As global energy demand rises, reliance on fossil fuels poses serious challenges, including greenhouse gas emissions and resource depletion. In response, substantial efforts are made to develop and adopt clean renewable fuel alternatives. Replacing fossil fuels with biofuels can significantly reduce emissions of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), and tropospheric ozone (O_3). Recent advances in the development of biofuels via genetic engineering have larger prospects for commercial-scale production. However, large-scale production remains challenging; therefore, to address this issue, it is vital to convert biomass into biofuels by developing revolutionary technology to improve biofuel production to meet present and future energy demands. The study aims to analyze alternative renewable energy sources and recent trends in the production of biofuel that are required to meet the demands of the global energy sector and economy while also considering future demand and utilization.

Keywords: Biofuel; Biomass; Fossil fuel; Renewable energy.

1. Introduction

The recent exponential expansion in industrialization and population has resulted in a worldwide energy crisis and concerns about reliance on non-renewable energy sources [1]. Fossil fuels, including coal, oil, petrol, diesel, natural gas, and mineral fuels partially derived from biological sources like bitumen and tar sand, account for 84% of the global primary energy consumption [2]. However, at current consumption rates, it is estimated that the worldwide supplies of petrol and oil will run out in about 50 years [3]. The movement of goods and people via air, sea, train, and road accounts for an estimated 58% of fossil fuel consumption [4]. Reducing dependence on fossil fuels and switching to renewable energy sources that are more ecologically friendly could help stabilize the climate, lower greenhouse gas emissions, and increase energy security. According to Yildiz [5] traditional biomass, primarily firewood and charcoal, supplies energy to 40% of the global population and makes up 11.5% of the world's primary energy source. While biomass is utilized for various applications, including the production of power, fuel additives, and agricultural applications, the domestic sector accounts for most of its use (75%), mostly for cooking and heating [6].

The remains of plants and animals that have been fossilized over millions of years due to heat and pressure in the earth's crust make fossil fuels. Commonly used fossil fuel derivatives include propane, kerosene, and gasoline [7]. Energy from fossil fuels is used for practically all human activities, including transportation, industrial processes, farming, building, and cooking. In addition to being used to create chemicals, fossil fuels (coal, oil, and gas) are also utilized to make

* Corresponding author: Abubakar Musa Shuaibu.

plastics, fertilizers, medications, and various other products. These processes' usage of fossil fuels has resulted in major side effects that are reason for concern worldwide. Pollutants such as carbon monoxide, carbon dioxide, nitrogen oxide, particulate matter, and sulphur oxide are released into the atmosphere. The main greenhouse gas that causes climate change is carbon dioxide. Additionally, acid rain has been formed due to the emission of sulphur and nitrogen oxides emissions from coal-fired power plants into the atmosphere, impacting both marine and terrestrial habitats. Ozone pollution is also caused by nitrogen oxide. Additionally, mercury, a heavy element that is beginning to pose a severe health risk, is released by coal-fired power plants [8]. Due to their long geological formation time and rapid depletion relative to production, fossil fuels are categorized as energy sources that are not renewable.

Jat *et al.* [9] estimate that with recent technology and continued consumption at current rates, the total amount of oil, natural gas, and coal that can be recovered globally is approximately 100 years, 30 years, and 18 years, respectively. The exponential increase in the population, combined with urban and industrial growth, implies that fossil fuels will likely run out very quickly. The steady reduction of fossil fuels and their non-biodegradable nature have prompted the search for alternate energy sources for potential future applications [10]. Due to the anticipated need for sustainable energy, biomass's contribution as a source of renewable energy supply attracted significant attention worldwide [11]. In contrast to fossil fuels, renewable sources can remain viable for prolonged periods and emit significantly fewer pollutants because they do not depend on burning to produce energy. Global CO_2, NO_x, and SO_2 emissions were reduced by 38%, 13%, and 70% in 2012 as a result of the integration of renewable energies [12]. As renewable energy technologies (RETs) advance and releases of greenhouse gases are controlled, the use of renewable energy solutions (RESs) is increasing. According to projections, RESs might provide 30–80% of the global energy demand by 2100 [13]. Air pollution from renewable energy sources is 3 to 10 times less harmful than that of fossil fuels [14].

1.1. Impacts of Fossil Fuel on the Environment

Climate change and global warming are two major environmental problems caused by GHG emissions, especially CO_2 emitted by fossil fuel power plant. Increases in extreme weather, changes in disease patterns, and harm to agriculture are all caused by climate change. According to estimates, about 150,000 deaths globally are attributed to climate change each year [15]. In addition, other pollutants released by conventional energy sources include carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), tropospheric ozone (O_3), and heavy metals (HMs). Oil and gas exploration generate a significant quantity of contaminants while processing and refining, which contributes to pollution in the air, water, and soil. Oil thermal power plants release a variety of pollutants into the environment, the most common is carbon dioxide which is 700–800 g CO_2/kWh on average and other pollutants comprise sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) [10].

When crude oil is refined into petroleum, volatile organic compounds (VOCs) (such as 2.5 g of benzene, toluene, and xylene per tonne of crude) are produced. The amount of pollution produced by this compound is largely determined by the final product. VOCs aid in the formation of smog in addition to being health hazards [16]. Coal is the most common and high-carbon fossil fuel. During the mining, processing, burning, and disposal of coal, pollutants, and greenhouse gases are emitted into the atmosphere. Carbon monoxide (CO), particle matter (PM), and hazardous organic compounds are among the hazardous indoor air pollutants that are released or produced when heating or cooking with polluting fuels like coal or biomass in open flames or conventional stoves [17]. Oil can introduce hydrocarbons, heavy metals, salts, and radioactive materials into the soil. These contaminants are discharged into the soil during the drilling, hydraulic fracturing, or transport processes, frequently as a result of equipment, casing, or pipeline failures [18]. Drilling for oil has the potential to contaminate groundwater and surface water when poisons and oil leak into aquifers via holes and cracks in the rock [19].

1.2. Biobutanol

Anaerobic bacteria are used in the butanol production process to produce acetone, butanol, and ethanol (ABE) in a ratio of 3:6:1. In the early years of the twenty-first century, biobutanol which is made from plant materials like starch and lignocellulose became more significant as a sustainable biofuel, leading to an increase in its use in the transportation and aviation sectors [20]. The selectivity of ABE fermentation, which uses a high product concentration and dilution rate to reduce the harmful effects of the solvent produced during fermentation, is a significant technological difficulty in the synthesis of butanol. The method becomes highly energy-intensive since the production of other products like acetone and ethanol limits the creation of butanol [21]. In 1862, Louis Pasteur became the first scientist to publish about the microbial production of biobutanol [22]. In the biphasic system of acetone-butanol-ethanol fermentation, butyric and acetic acids are produced through the acidogenesis phase. Following the generation of acids, these acids are reassimilated, generating solvents such as acetone, butanol, and ethanol. Nevertheless, other solvents are synthesized concurrently with the butanol production process, which lowers the target product's selectivity rate [23]. It has been reported that scientists used *C. saccharoperbutylacetonicum* to produce biobutanol by using algal biomass that was removed from effluent including enzymes like cellulases and xylanases. Green seaweed has also been used to metabolize xylose and glucose as well as produce biobutanol with the strains of *C. acetobutylicum* and *C. beijerinckii*. Marine macroalgae, such as Ceylon moss, have been demonstrated to be a viable option for the synthesis of butanol. To extract biobutanol from these macroalgae, clostridial strains were utilized as feedstock [24]

1.3. Biohydrogen

The microorganisms produce biohydrogen as a by-product of a wide variety of metabolic reactions. Biohydrogen is a highly efficient sustainable energy source that has a short half-life [25]. It can alleviate the strain that comes from a limited supply of alternative resources. The biophotolysis of water with microalgae and anaerobic fermentation of biomass high in carbohydrates is a potential approach to produce biohydrogen [26]. The transformation of polymeric sugars into monomers is thought to be a restricting phase of the manufacturing procedure since monomers are widely used in the synthesis of biohydrogen. Polymeric sugars are de-polymerized via a variety of pre-treatments, which are used in combination to maximize hydrogen production from algae. The dark fermentation process leaves a difference between the energy required to make biohydrogen and the energy that is generated as hydrogen with a negative net energy balance. To make this entire process economically feasible, it is imperative to combine the algal dark fermentation process with a biorefinery approach in which the outputs are converted into useful proteins [27].

1.4. Bio-oil

The potential of algal biomass to produce bio-oil is quite promising because of its sustainable and clean nature [28]. Bio oil is a liquid fuel that is produced through thermal degradation (such liquefaction or pyrolysis) of biomass. In addition to being processed further to create biodiesel or other biofuels, it can be utilized straight as a fuel for heating. Bio-oil functions as a source for high-value chemical compounds, such as aromatic compounds, because of its rich content of compounds produced by the decomposition of cellulosic, hemicellulosic, or lignin biomass [29].

1.5. Biodiesel

Biodiesel constitutes an oxygenated fuel that generates a complete combustion and has less negative environmental effects with great emission control. A wide range of feedstocks, including used cooking oils, animal fat, and oilseeds like canola and oil palm, can be used to make biodiesel [30]. Transesterification is the most often utilized procedure for producing biodiesel. During this process, long-chain fatty acids in triglycerides from vegetable and animal fats are converted into molecular molecules. Triglycerides, also known as fatty acids, are formed when three fatty acids are linked together by the carbon-carbon bonds. When these carbon bonds are broken, as illustrated in Figure 1, each triglyceride molecule is transformed into fatty acid ester molecules and glycerol, which can be processed to produce biodiesel[31].

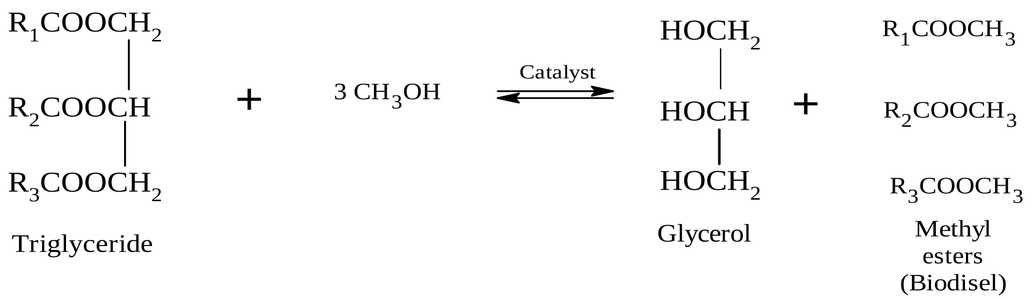

Figure 1 Process of transesterification of triglycerides to produce biodiesel.

1.6. Bioethanol

The ecological benefits of bioethanol have drawn significant attention to it in the modern world. Algal, lignocellulosic, and plant biomass can all be used as feedstocks for the production of bioethanol [32]. When producing bioethanol from algal biomass, the algae are collected and subsequently dried to eliminate nearly its water content, allowing for the easy handling and production of a solid material. The harvested algae are subjected to an appropriate dehydration procedure to remove the water content prior to the fuel extraction[33].

The most common method of converting the starch and sugars in algal biomass into bioethanol is fermentation, which produces bioethanol from the biomass. It involves breaking down the biomass and converting the starch into sugars, which are then mixed with water and yeast in bioreactors called fermenters [34]. Yeast is utilized because it converts sugar to bioethanol. The concentrated ethanol is subsequently drained and converted into a fluid state by distillation, which is employed as a purification technique to eliminate water and other impurities from the diluted alcohol [35]. Utilizing microalgae in the production of bioethanol can help address environmental issues in situations where the conventional feedstock used in bioethanol production is found to emit more greenhouse gases during the process of manufacture and application than fossil fuels [36]. The generation of bioethanol from waste sugar beetroot pulp is modeled by [37] to use it to assess novel technologies and goods that utilize lignocellulosic raw materials. A bioethanol production plant that processes approximately 17,000 tonnes of waste sugar beetroot pulp annually can have its capital and operating expenses calculated using the established model. Additionally, it is capable of projecting the biotechnological process and economic indicators, calculating the contribution of key components to the cost of producing bioethanol, and contrasting several model scenarios for co-product processing [38]

2. Classification of Biofuels

Biofuels are classified as conventional or advanced fuels based on the materials utilized to create them, their constraints as a renewable source, and technological advancement [39]. Advanced biofuels are second, third, and fourth-generation fuels, whereas traditional biofuels are commonly referred to as fuel from first-generation [40].

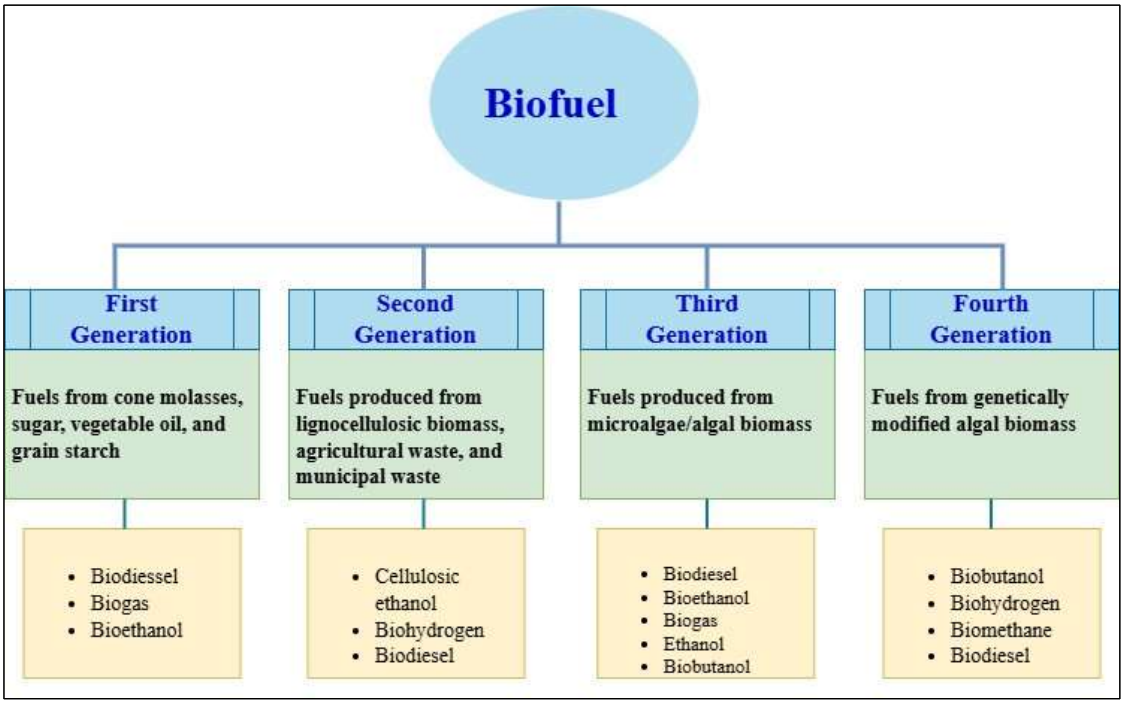

Figure 2 Biofuel types, sources, and generation.

2.1. First Generation

First-generation biofuels are made from biomass, which comprises vegetable lipids and oils, sugar, and starch. These fuels are derived straight from food sources [41]. The initial generation of biofuels has extremely complicated production technologies [42]. In particular, biorefinery facilities employ maize grain as a feedstock to produce biofuel or bioethanol. A hammer milling device is used in biorefineries to process maize, allowing for further chemical reactions and fermentation to produce biofuel. The GHG emissions for first-generation biodiesel vary significantly between life cycle assessment (LCA) studies, with global warming potential (GWP) ranging from 3 to 111 g CO_2 eq. MJ^-. However, when all feedstocks are taken into account, the average GWP of biodiesel is lower than that of fossil diesel. Nonetheless, only palm oil-based biodiesel meets the renewable energy guidelines RED criteria for a 65% reduction in GWP relative to diesel [43].

2.2. Second Generation

These are based on techniques that convert agricultural lignocellulosic biomass into fuels through biochemical or thermochemical [44]. Wastes (such as municipal solid wastes), by-products (such as cereal straw and forest residues), and dedicated feedstocks (such as vegetative grasses and other energy crops), are lignocellulosic feedstocks that can be used to produce second-generation biofuels [45]. Plants and agricultural non-food materials are frequently used to extract these sugars. In contrast to grains, cellulose, lignin, and polyose are among the several chemical compositions that make up cellulosic biomass [46].

2.3. Third generation

Third-generation biofuel has several advantages over first and second-generation biofuels, including improved and modern production techniques and a low return on investment. Photosynthetic organisms including diatoms, cyanobacteria, and Euglena are the source of third-generation biofuels. They can grow easily in freshwater, saltwater, and industrial waste [47]. The raw material increases at a rate more than 20-30 times quicker than previous generations of biofuels. Jeswani, *et al*. [48] report that the quantity of oil from algae is thirty times higher than the basic components of other biofuel crops.

2.4. Fourth generation

Biofuels classified as fourth-generation are those that are created by the genetic engineering of algae [49]. Macroscopic and microalgal biomass, as well as cyanobacteria, are the main sources of feedstock for fourth-generation biofuels. In contrast to microalgae and macroalgae, which belong to the kingdom Protista and have a nucleus surrounded by a membrane, cyanobacteria are prokaryotes (having membrane-bound organelles and being members of the kingdom Bacteria). Blue-green algae, Bacillariophyceae, Eustigmatophyceae, and Chlorophyceae are the microalgae employed in the manufacture of algal biofuel [50].

3. Biomass to Biofuel

Biomass is a diverse energy supply for biofuels; this has been obtained from various sources, Fig. 3, nonetheless, its biochemical structure and composition have a significant impact on biofuel productivity, therefore understanding its primary chemical structure is critical. The plant cell wall is made mostly of lignin, cellulose, and hemicellulose, with trace amounts of inorganic materials [51]. The use of biomass has continued to be a significant source of energy and influences the environment and society locally, regionally, and worldwide [52]. Utilizing cutting-edge biofuel production methods to recover energy from biomass has significant promise for enhancing global energy security and reducing trade deficits [53]. Many attempts are being made globally for the utilization of biomass as a fuel in both traditional and modern times. According to extensive source data provided by the Renewable Energy Statistics (2020), the overall renewable energy generation and capacity in 2019 was 2533 GW [54].

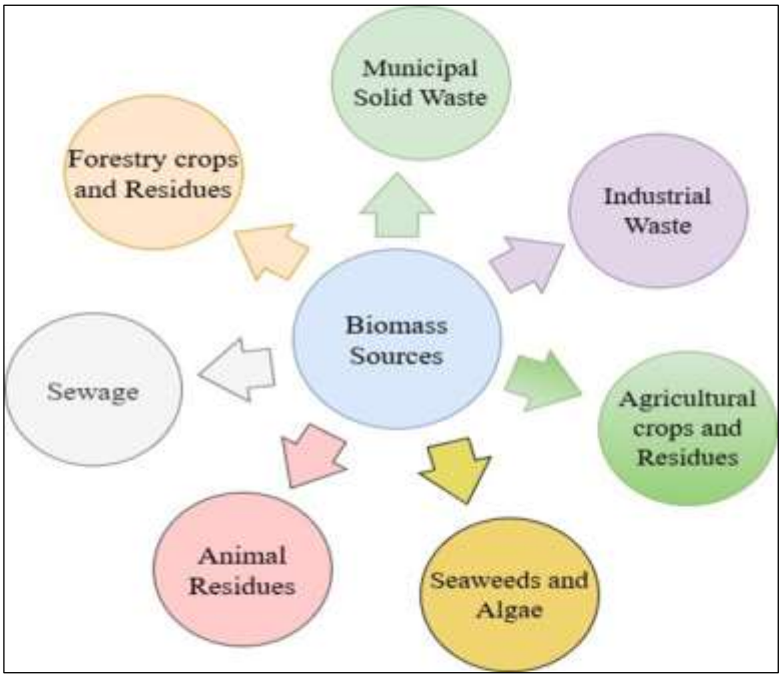

Figure 3 Sources of biomass for biofuel production.

The advance of innovative biomass systems that aid the efficient production, conversion, and utilization of biobased products in close harmony with the natural world is a daunting task that must be undertaken to maximize the utilization of biomass [55]. Any lignocellulose that is to be converted to biofuel must undergo an additional pre-treatment procedure in order to liberate the fermentable sugars. To prepare the cellulose surface for enzymatic hydrolysis, a sophisticated pre-treatment procedure is used to fractionate various components of the cell wall found in the biomass, such as hemicellulose and lignin [56]. The pre-treatment is impacted by several aspects such as feedstock type, biomass structure, enzyme strain, chemical components of the biomass, and generation of inhibitory compounds [57]. Recently, biomasses are utilized to generate a range of liquid and gaseous biofuels, such as bio-oil, ethanol, methanol, and biodiesel [58] Figure 4. These biofuels have shown a significant potential for establishing sustainable energy security and providing energy in the future [59].

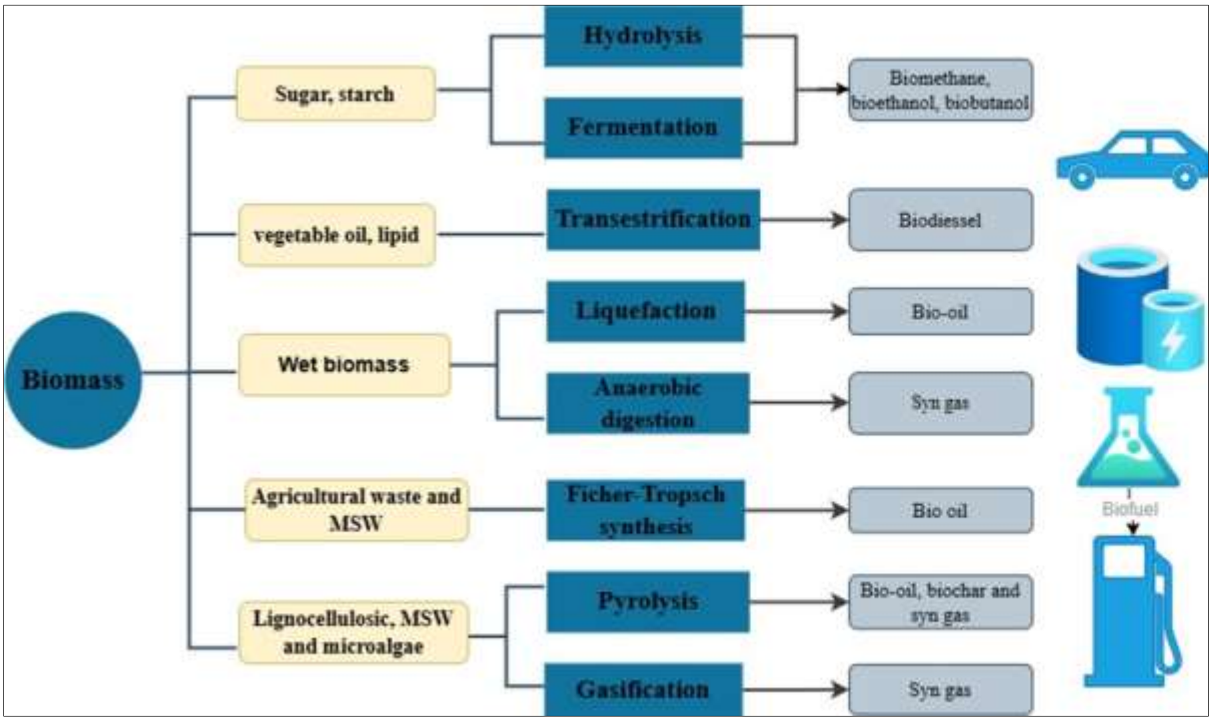

Figure 4 Biomass conversion to biofuels.

3.1. Production Processes of Biofuel

Two primary methods can be effectively employed to transform biomass into biofuels. These include biochemical and thermochemical processes [60]. In a biochemical process, enzymes and other microorganisms are used to modify the cellulose and hemicellulose components of the feedstock into sugars, which, after fermentation, yield ethanol. Anaerobic digestion, fermentation, and transesterification are the three main biochemical processes that convert biomass to biofuel. Yeast, fungus, and bacteria are all involved in biochemical conversion. In this case, the microorganisms' generated enzymes are crucial in dissolving the biomass structure biopolymers into liquid or gaseous biofuels, like hydrogen, ethanol, and biogas [61]. Microbes or enzymes can be used in a biochemical process to convert biomass, allowing it to be broken down into fuels. Biochemical conversions often happen more slowly and need less energy than thermochemical conversion techniques, Table 1 [62].

Table 1 Biochemical conversion process.

Technology	Feedstock	Operation condition	Product	Advantages	Disadvantages	References
Transesterification	Microalgal biomass, waste oil, animal fat	Temperature 50-70°C, Acidic, basic, or enzymatic catalysts	Liquid fuel, biodiesel	Low process temperature, environment ally friendly, and high yield	Requires further processing	[63]

		(commonly NaOH, KOH, or lipase enzymes)				
Fermentation	Microalgal biomass, Corn, wheat, cassava	Usually carried out in the absence of oxygen	Alcohol(ethanol) and CO_2	Energy efficient, environment ally friendly	Slow reaction, microbial inhibition	[64]
Anaerobic digestion	Food waste, agricultural residues, manure.	Optimal pH is around 6.5 to 7.5 in an anaerobic condition	Biometh ane, CO_2, digestat e	Safe disposal of digestate and nutrient recovery	Long retention time, complex system design	[65]

Thermochemical also referred to as biomass-to-liquids is an emerging technique for transforming biomass into fuel. The process uses pyrolysis, gasification, and liquefaction to produce synthesis gas ($CO + H_2$) Table 2, which is then used to reform a variety of long carbon chain biofuels, including ethanol and synthetic diesel [66]. Lignocellulosic biomasses can be converted by a variety of thermo-chemical processes to produce energy and other products like heat, syngas, liquid biofuels and solid charcoal, that depend on temperature, pressure, and heating [67].

Table 2. Thermochemical conversion processes.

Technology	Feedstock	Operating condition	Product	Advantages	Disadvantages	References
Pyrolysis	Lignocellulosic biomass	Temperature 400-600^{0}C and N_2 flow rate and 5^{0}C/min residence time	Syngas, biochar, and bio-oil	Versatility, and efficiency	High operating and investment costs	[68]
Gasification	Municipal plastic waste (MPW), algae-based biomass	Fluidize bed gasifier, temperature 800-1100^{0}C	syngas	Flexible and high emission control	Complex multistage processing and formation of tars and chars	[69]
Liquefaction	Algal biomass (microalgae)	Temperature range 300-350^{0}C	Crude bio-oil	High yield and quality bio-oil, feedstock versatility	High energy consumption process with longer residence time	[70]
Ficher–Tropsch synthesis	Municipal sewage waste, agricultural residue, algal biomass	Temperature range 200-350 ^{0}C, and pressure range 10-40 bar	Diesel and hydrocarbons such as alkane, alkene, and paraffin	Environmentally friendly, low sulphur content	Energy intensive, GHG emission	[71]

3.2. Global Biofuel Production

Global biofuel production has reached approximately 190 billion liters annually and is predicted to rise significantly. The production of biofuel evolved globally between 2007 and 2017 at an annual rate of 11.4% [73]. According to the IEA, the generation of biofuel rinsed by 10 billion liters globally in 2018 to reach 154 billion liters. By 2024, this amount is estimated to have increased by 25%, with a projected annual growth rate of 3%. Notwithstanding, the bioenergy industry encounters noteworthy difficulties, such as unpredictability surrounding crude oil prices, political hazards, fiscal impediments, and surpassing projected scientific barriers for the commercialization of advanced biofuels [74]. Despite these obstacles, the biofuel sector is expanding and taking up a larger portion of the global energy consumption; this has resulted in the creation of almost 2.8 million employment and shows how important the sector is to job growth. In 2023, the United States emerged as the primary producer of biofuel, with a production volume of 1,795 petajoules. Brazil and Indonesia were second and third, with approximately 1,016 and 433 petajoules, respectively. In contrast, Germany was the main producer of biofuel in Europe, with its production amounting to almost 160 petajoules that year, ranking it among the top five nations in the world [75].

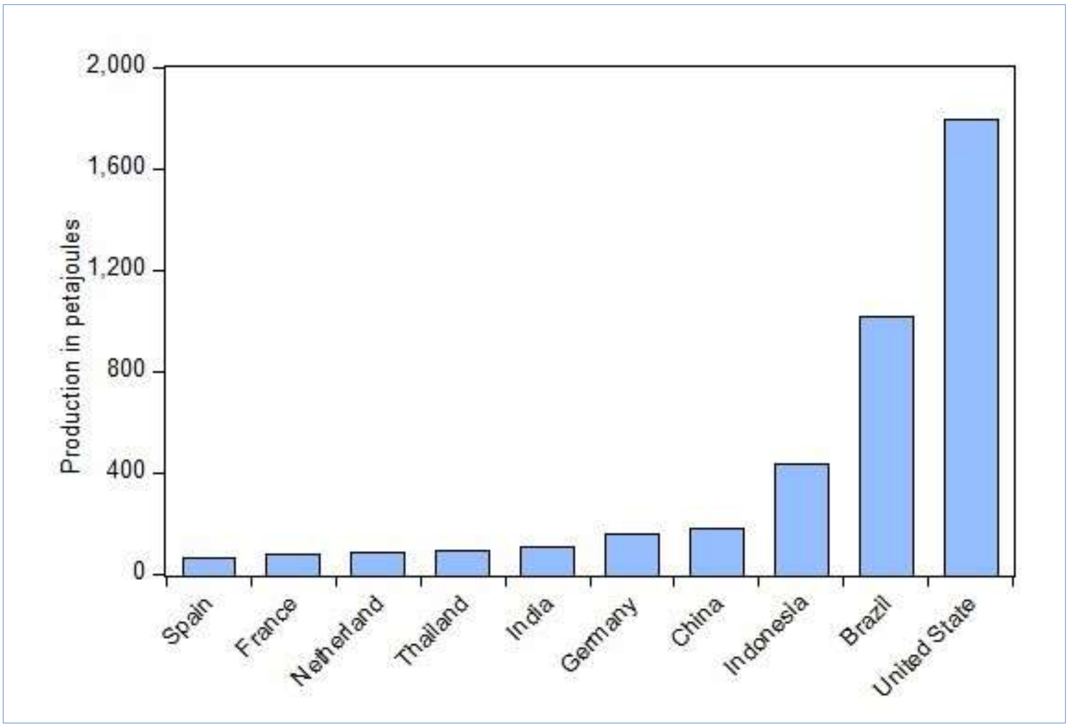

Figure 5 Global biofuel production by country in 2023 [75].

The European Union's council and parliament came to a tentative agreement in March 2023 over the update of the Renewable Energy Directive (RED III) (Reis, 2023). Strengthening sustainability standards for biomass energy usage by implementing the cascading principle and taking into account national priorities is part of the agreement. In September 2022, the EU established the biomethane industrial partnership with the aim of assisting in the achievement of its 2022 target of 35 billion cubic meters of annual biomethane generation by 2030 (as opposed to the current 3.5 billion cubic meters) (Adsul, 2020). The Inflation Reduction Act (IRA), which was launched in 2022, provides funding for a number of steps in the bioenergy value chain. These include increasing the utilization of waste materials and sustainable biomass in the US to generate sustainable aviation fuels, chemicals, and biomaterials, such as advanced fertilizers, and to promote innovation in these fields, including conversion technologies. India's biomass program was extended in 2022 to facilitate the production and use of household solid and gaseous biogas through 2026 [74].

The output of biofuels worldwide attained 960 thousand barrels of oil equivalent per day in 2023, a significant rise from the 12 thousand barrels of oil equivalent per day generated in 2000. Policies that promote the use and production of biofuels have been a major factor in growth because of the belief that they can reduce GHG emission in relevant sectors and offer energy security [76]

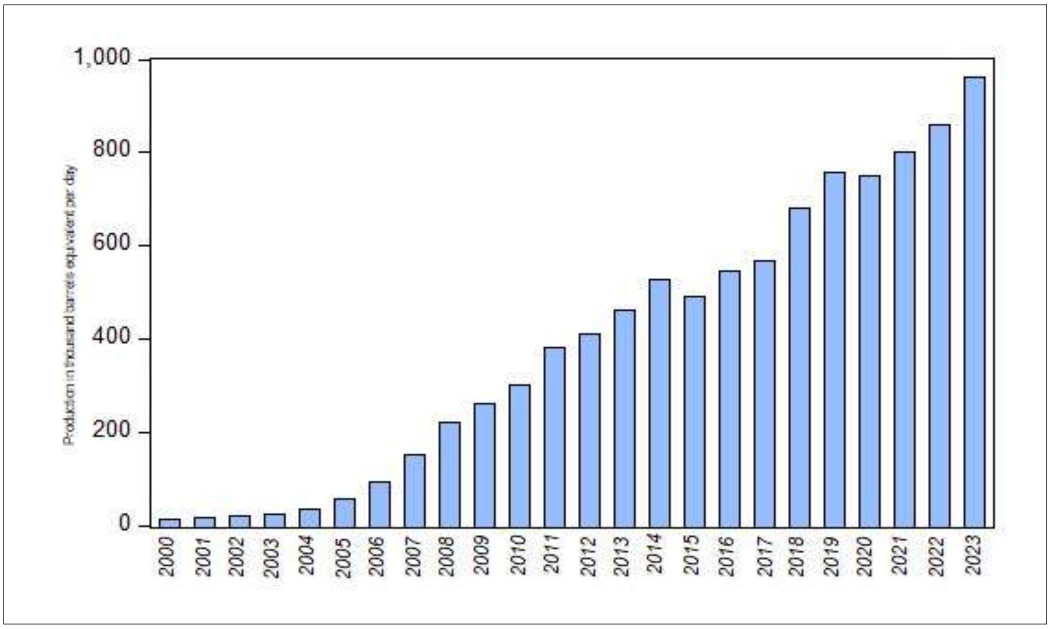

Figure 6 Biofuel production worldwide from 2000 to 2023 [76].

3.3. Global Biofuel Consumption Trends

The National Biofuels Policy (NBP) has been created to capitalize on the several environmental, public, and commercial aids that result from large-scale biofuel output which comprises 64 countries, 27 from Europe, 13 from the United States, and 12 from Asia [77]. NBP had mandated that 20% of petrol and diesel be blended with biofuel to lower pollution without changing the engine by the close of 2017. However, the government was unable to meet these objectives due to a lack of biofuel availability. Based on current energy policy forecasts, India's energy consumption is projected to double over the subsequent 20 years, from 750 MT in 2011 to 1469 MT in 2030 [78]. From this angle, liquid biofuels are a viable fossil fuel substitute to meet the energy demand of the transportation sector. According to the most recent analysis, the demand for biofuel is predicted to climb sharply and consistently until 2045, reaching an estimated 257 to 500 billion liters annually by the end of 2030. According to the global biofuel context, the overall demand for liquid biofuel in 2035 might range from 3280 to 4350 billion liters [79]. An evaluation of statistical significance of global energy consumption is anticipated to show increases in a few countries, mostly in the United States. When comparing the production and consumption of energy on a worldwide scale in 2019 and 2030, a sustainable method shows how it will be used. Factors impacting the worldwide demand for biofuels include the expansion of fleet vehicles, the need for transportation services, and the replacement of alternative fuel sources like electricity. According to a research conducted by the International Energy Agency (IEA), the demand for biofuel is anticipated to rise to 4600 billion liters yearly by 2045 [80]. The need for biofuels in the US and the EU is not expected to fulfil the 2030 Sustainable Development Scenario (SDS) requirement, despite the most recent technological advancements. This might be the result of variables like the low proportion blend, the use of high-efficiency vehicles, and the use of biofuels, which are expected to cause a decline in consumption. However, to meet the demand for SDS, biofuel production rates are expected to rise annually [81].

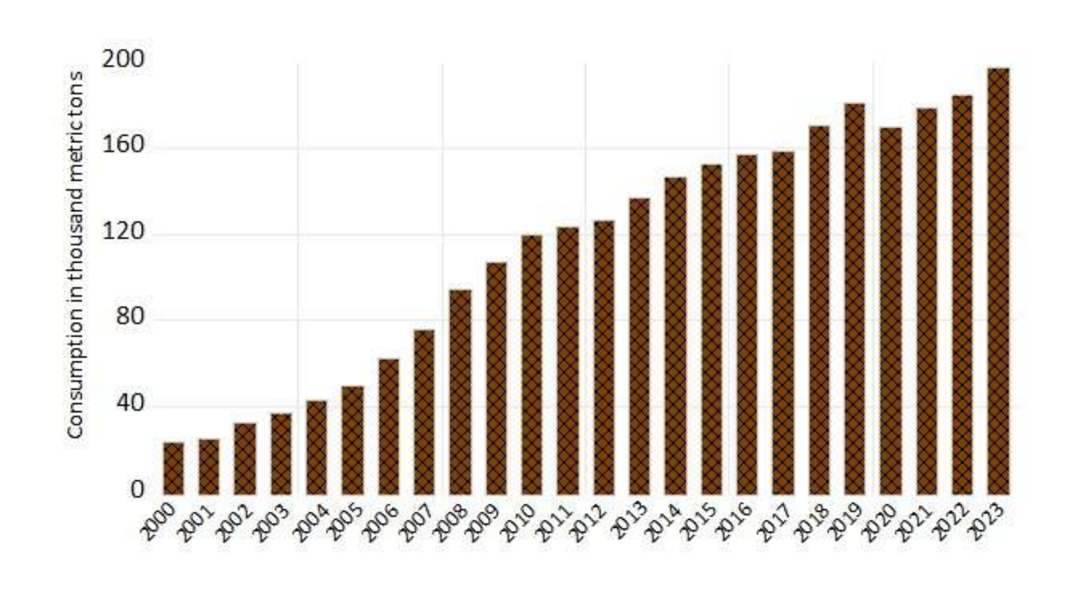

Figure 7 Global biofuel consumption from 2000 to 2023 [82].

3.4. Evolution of Biofuels as an Energy Source

Since 1900, biofuel has been used as a fossil fuel substitute [83]. The production of biofuels from various bioresources by using cutting-edge technology and biological processes is becoming progressively more widespread. Exploiting agricultural crop wastes and biomass waste to generate biofuels is anticipated to lower environmental impact and address a number of environmental concerns, such as trash management [84]. Early 20th-century bioethanol and biodiesel production involved the use of vegetable oils like sunflower, palm, and soybean oil along with cellulose or starch-based biomass such as wastes from the food sector, soybeans, and cereal grains [85]. Lignocellulose, starchy, and algal biomass are now well recognized as among the various sources used to produce bioethanol, biodiesel, and biobutanol. These sustainable feedstocks are abundant in nature and have an estimated annual production of 200 billion tonnes worldwide [86]. The first-generation feedstock has been demonstrated previously to be an effective substrate to produce biofuel when fermented with mechanical pre-treatment and thermal pre-processing. Nevertheless, the high rate of these feedstocks can have a direct influence on food supplies, and the distribution of agricultural land has contributed to the unethical and costly availability of these feedstocks [87]. According to Hassan *et al.* [88], edible food crop resources like sugarcane, potatoes, oilseeds, corn, barley, wheat, and soybeans were used to make the first generation biofuels, which included biodiesel and bioethanol. Accordingly, utilizing fungal mycelia as an enzyme during fermentation of ethanol was the initial chemical energy source created by biofuel from maize and sugarcane [89]. Dalena *et al.,* [90] published the same finding, demonstrating that raw maize flour may be used to produce ethanol fermentation through the use of starch-digesting microorganisms such as *Rhizopus sp*. and *Saccharomyces cerevisiae*. Thus, using early enzymatic hydrolysis methods, a massive amount of bioethanol was produced on a big scale from starch in the first generation. The biofuels from second generation involves using readily accessible lignocellulosic materials and various organic waste products (such as wood, straw, switchgrass, and oilseed) to create the fuel. Algae are used as a feedstock in third-generation biofuels, which provide a significant amount of lipids needed to make biodiesel and other biofuels. Nonetheless, the production of biofuels for the fourth generation relies on genetically engineered organisms, altered metabolic pathways, increased CO_2 fixation capacity, and microalgae post-genome technologies [91].

3.5. Environmental Benefits and Challenges of Biofuel

Compared to fossil fuels, biofuels have several benefits. When creating standards for assessing the consequences of the biofuel industry, it is crucial to consider environmental challenges and associated difficulties such as biodiversity, soil and water resources, air pollution, GHG emissions, and sustainability [92]. These environmental implications are frequently assessed using LCA [93]. Presently, the majority of biofuel manufacturing companies evaluate the ecological impact by using LCA to make necessary process adjustments. These adjustments should primarily target lowering emissions during the production process. It is critical to seize chances and find long-term solutions to environmental problems to further socioeconomic growth [14]. Exploiting biofuels as a renewable energy source lowers the quantity of GHGs released into the atmosphere while burning. This minimizes pollution load and other environmental effects.

The generation and consumption of biofuels are potentially carbon-neutral since they are derived from biomass, which utilizes the majority of CO_2 emitted into the environment [94].

The goal of sustainable biofuel production is to maximize its potential as a low-carbon substitute for traditional fossil fuels while minimizing adverse impacts on the natural environment and society [95]. Lessening GHG emissions, diversification of energy sources, waste administration, forest preservation, energy independence, and social sustainability are just a few of the major benefits of biofuel in a nation that embraces the sustainability paradigm [96]. Several studies on the sustainability of biofuel have been published to reduce energy scarcity and climate change. The effects of biofuel on the energy water food (EWF) connexion globally were examined by Chong *et al.* [97]. Their goal was to assess the sustainability of biofuel and find an understanding of the complex linkages that exist between the environment. The results provide useful information for governments creating environmental policy frameworks to support the use of biofuel technological innovation as a greener alternative to traditional fossil fuels. Industrial biofuel production from agricultural crops resulted in water scarcity, fast and irreversible soil degradation, excessive use of fertilizers and pesticides that contaminated the air and water, and a decline in both agricultural and wild biodiversity [98].

In general, biofuel emits less PM, CO, hydrocarbons, and VOCs from exhaust than fossil fuel, but more NOx [99]. The disparities become more pronounced at higher percentages of biofuel, but they are minor at 5-to 20% blends and would have no detectable effects on air quality [100]. However, [101] contends that because biofuel exhaust has a larger percentage of ultra-fine particles (lower than 100 nm diameter) than fossil fuel exhaust, it may be more hazardous to human health even though its PM emissions are lower. This is because smaller particles can enter the lungs more deeply, stay in the air longer, and be easier to breathe in. Other evaluations of the possible health effects of biofuel, however, indicate that there aren't many differences in the effects when using biofuel fuel mixes instead of fossil diesel. Thus, the issue of how biofuels affect human health is still up for debate and needs more data and research [102]. Although producing ethanol from trash does not directly compete with farmland or biodiverse areas, it may affect ecosystem services and biodiversity. Agricultural and forestry waste extraction, for example, can have a detrimental influence on species that consume decomposing biomass, lower soil carbon stocks and fertility in cultivation regions, and indirectly increase deforestation as a result of rising biomass demand [103]. However, planting native perennials on low-biodiversity or degraded lands could improve the provision of several ecosystem services, such as pollination and carbon storage, as well as lower fertilizer and pesticide use compared to conventional crops, permitting the persistence of species found in grasslands or shrublands, and lessen competition with food crops [104].

3.6. Economic Viability and Market Trends

The economy, environment, and public health are all impacted by biofuels in different ways [105]. According to some studies, governments everywhere must carefully weigh these effects before making any new investments in or plans for the use of biofuels [106]. Expanding the biofuel industry can improve a country's economic security, particularly by creating jobs in rural and disadvantaged areas [107]. Furthermore, not all nations have enormous crude oil reserves, therefore shifting to biofuel production would allow governments to lower their dependence on fossil fuels and, as a result, their importation costs. Thus, it was anticipated that Brazil produced 17.4 billion liters of biofuel between 2005 and 2014, saving 12.9 billion US dollars in fossil fuel importation expenditures [108]. When producing biodiesel, the utilization of locally available feedstock, such as food waste or palm oil can be encouraged by the sustainability paradigm. This might boost local farmers' incomes and create new investment prospects in the bioenergy industry. The biofuel sector is still growing and contributing more to the world's energy consumption despite all of these factors. The bioenergy sector generated almost 2.8 million employment, demonstrating its contribution to job creation [109]. The social and economic elements of biofuels are related to the demand for liquid fuels eventually, which is expected to boost incomes wealth, and as well socioeconomic advantages. Many countries diversify their energy mix to ensure the rural and regional services from indigenous biofuel production and its use [110].

Biofuel production and consumption contribute to regional and national energy security, economic development and diversification, and import substitution, with direct and indirect effects on the trade balance, power supply, and diversification through the emergence of novel industries. The generation economy of biofuel through the fermentation process depends on the nature of feedstock and hence focus is switched towards forest waste and agro-waste being non-food crops with a high proportion of cellulose and have been researched extensively in recent years [111]. Statista (2020) estimates that 2,063,000 biofuel-related jobs have been generated worldwide in 2018. The maximum employment was generated in Brazil (832,000), followed by the United States (311,000), China (51,000), and India (35,000). The process's economy is determined by the type of waste, disposal alternatives, and any other potential uses, with any waste available at a low cost encompassing massive scale-up capacity. Therefore, the establishment of a large-scale, workable, and effective feedstock impart chain is essential to the development of liquid biofuel [112].

3.7. Technological Advancements and Innovations

The optimization of recent biofuel-production technology for higher productivity and effectiveness of lignocellulosic biomass transformation, diversification of feedstocks to ensure the feasibility of biofuel production within current ecological and economic constraints (such as carbon fixation by photosynthesis and electrochemistry, as well as the value-added product development of biowaste), and the development of designer molecules that increase performance and fuel efficiency while lowering carbon emissions [113]. To offer long-term, reliable, and affordable production systems for the biofuel sector, significant efforts must be made to incorporate social, economic, and environmental considerations in addition to addressing technological constraints [114]. Globally, there is a rising trend in producing biofuels from various bioresources through the incorporation of innovative technology and biological methods [115]. Innovation in the creation of sophisticated biofuel products with enhanced compatibility and performance is also being fuelled by new technology. For example, manufacturing drop-in biofuels is becoming more popular. These fuels are chemically identical to conventional fuels and can be easily incorporated into engines and fuel infrastructure already in place [116]. Utilizing cutting-edge catalytic processes and refining techniques, advanced biofuel products such as renewable diesel, bio-based jet fuels, and biobased chemicals are being developed to provide a more sustainable and ecological option to conventional petroleum-derived fuels [117]. Advances in fermentation and enzymatic hydrolysis are two examples of recent technological developments in biofuel production that have led to more effective biofuel processing technologies. Enhancing feedstock properties and streamlining production methods are two ways that biotechnology and genetic engineering can transform the production of biofuels [118]. Through the use of genetic engineering, crop characteristics like as biomass yield, stress tolerance, and nutrient utilization can be modified. This process results in the development of feedstocks that are more resilient and energy-dense, making them ideal to produce biofuels [119]. The efficient transformation of complex biomass to biofuels is made possible by biotechnological developments like the use of genetically modified microbes and enzymes [120]. This makes it easier to design ecologically friendly and economically viable biofuel production processes. Moreover, biotechnology can help build customized microbial strains that can generate valuable biofuels and bioproducts from different feedstocks, such as waste streams and lignocellulosic materials [121]. Researchers and industry stakeholders can unleash the feasibility of biofuels as clean, renewable, and scalable energy solutions by utilizing genetic engineering and biotechnology to overcome the inherent limitations of traditional biofuel manufacturing processes, such as low transformation efficiencies and substrate specificity [122]. Unprecedented breakthroughs in feedstock cultivation, conversion technology, and product development are being driven by technological advancements and innovations in the biofuel business. The efficiency and sustainability of biofuel production are being improved by recent advancements in precision agriculture, biotechnology, and sophisticated processing methods, making biofuels a more attractive and competitive substitute for traditional fossil fuels [123]. The biofuel sector can keep developing and help the world move towards a more ecologically friendly and sustainable energy system by utilizing cutting-edge technologies and adopting a multidisciplinary strategy [124].

4. Conclusion

In conclusion, the environment is harmed by the use of fossil fuels, and the need for energy is growing faster as a result of rising tendencies in industrialization, economic development, and population expansion. Enhancing the effectiveness and sustainability of biofuel production requires technological developments in biomass conversion and integration with other renewable energy sources. Biofuels provide a feasible path to a more sustainable and clean energy future. It could open up economic prospects for poor countries and countries that depend on oil imports. Therefore, by using agricultural resources, biofuels have the ability to increase economic growth, lessen dependency on petroleum oil imports, and limit the generation of greenhouse gases and pollutants. Increased development of these fuels will probably benefit the world economy and slow down climate change. To accurately assess whether these fuels are a sustainable substitute to fossil fuels, more research is needed to ascertain the impact of the fuels on global public health, develop standardized assessments of the environmental effects of the biofuel production systems, improve estimates of the feasibility and yield of potential production, and develop integrated assessments to comprehend the socioeconomic and ecological implications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Reference

[1] V. G. Yadav, G. D. Yadav, and S. C. Patankar, 'The production of fuels and chemicals in the new world: critical analysis of the choice between crude oil and biomass vis-à-vis sustainability and the environment', *Clean Technol. Environ. Policy*, vol. 22, no. 9, pp. 1757–1774, Nov. 2020, doi: 10.1007/s10098-020-01945-5.

[2] C. Acar and I. Dincer, '1.30 Future Energy Directions', in *Comprehensive Energy Systems*, Elsevier, 2018, pp. 1199–1214. doi: 10.1016/B978-0-12-809597-3.00139-5.

[3] P. Achakulwisut, P. Erickson, C. Guivarch, R. Schaeffer, E. Brutschin, and S. Pye, 'Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions', *Nat. Commun.*, vol. 14, no. 1, p. 5425, Sep. 2023, doi: 10.1038/s41467-023-41105-z.

[4] J. C. Escobar, E. S. Lora, O. J. Venturini, E. E. Yáñez, E. F. Castillo, and O. Almazan, 'Biofuels: Environment, technology and food security', *Renew. Sustain. Energy Rev.*, vol. 13, no. 6–7, pp. 1275–1287, Aug. 2009, doi: 10.1016/j.rser.2008.08.014.

[5] İ. Yıldız, '1.12 Fossil Fuels', in *Comprehensive Energy Systems*, Elsevier, 2018, pp. 521–567. doi: 10.1016/B978-0-12-809597-3.00111-5.

[6] P. Nejat, F. Jomehzadeh, M. M. Taheri, M. Gohari, and M. Z. Abd. Majid, 'A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries)', *Renew. Sustain. Energy Rev.*, vol. 43, pp. 843–862, Mar. 2015, doi: 10.1016/j.rser.2014.11.066.

[7] U. Lawan Muhammad, 'Biofuels as the Starring Substitute to Fossil Fuels', *Pet. Sci. Eng.*, vol. 2, no. 1, p. 44, 2018, doi: 10.11648/j.pse.20180201.17.

[8] S. K Ghosh, 'Fossil Fuel Consumption Trend and Global Warming Scenario: Energy Overview', *Glob. J. Eng. Sci.*, vol. 5, no. 2, Apr. 2020, doi: 10.33552/GJES.2020.05.000606.

[9] H. S. Jat *et al.*, 'Energy use efficiency of crop residue management for sustainable energy and agriculture conservation in NW India', *Renew. Energy*, vol. 155, pp. 1372–1382, Aug. 2020, doi: 10.1016/j.renene.2020.04.046.

[10] A. Shahsavari and M. Akbari, 'Potential of solar energy in developing countries for reducing energy-related emissions', *Renew. Sustain. Energy Rev.*, vol. 90, pp. 275–291, Jul. 2018, doi: 10.1016/j.rser.2018.03.065.

[11] R. Saengsuriwong, T. Onsree, S. Phromphithak, and N. Tippayawong, 'Conversion of tobacco processing waste to biocrude oil via hydrothermal liquefaction in a multiple batch reactor', *Clean Technol. Environ. Policy*, Jun. 2021, doi: 10.1007/s10098-021-02132-w.

[12] J. Novacheck and J. X. Johnson, 'The environmental and cost implications of solar energy preferences in Renewable Portfolio Standards', *Energy Policy*, vol. 86, pp. 250–261, Nov. 2015, doi: 10.1016/j.enpol.2015.06.039.

[13] V. G. Yadav, G. D. Yadav, and S. C. Patankar, 'The production of fuels and chemicals in the new world: critical analysis of the choice between crude oil and biomass vis-à-vis sustainability and the environment', *Clean Technol. Environ. Policy*, vol. 22, no. 9, pp. 1757–1774, Nov. 2020, doi: 10.1007/s10098-020-01945-5.

[14] A. shasavari, A. Karimi, M. Akbari, and M. Alizadeh Noughani, 'Environmental Impacts and Social Cost of Non-Renewable and Renewable Energy Sources: A Comprehensive Review', *J. Renew. Energy Environ.*, vol. 11, no. 1, Jan. 2024, doi: 10.30501/jree.2023.382598.1545.

[15] 2023 WHO, 'https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health'. 2023. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

[16] E. Rokni, X. Ren, A. Panahi, and Y. A. Levendis, 'Emissions of SO2, NOx, CO2, and HCl from Co-firing of coals with raw and torrefied biomass fuels', *Fuel*, vol. 211, pp. 363–374, Jan. 2018, doi: 10.1016/j.fuel.2017.09.049.

[17] B. Wang, Q. Wang, Y.-M. Wei, and Z.-P. Li, 'Role of renewable energy in China's energy security and climate change mitigation: An index decomposition analysis', *Renew. Sustain. Energy Rev.*, vol. 90, pp. 187–194, Jul. 2018, doi: 10.1016/j.rser.2018.03.012.

[18] J. Pichtel, 'Oil and Gas Production Wastewater: Soil Contamination and Pollution Prevention', *Appl. Environ. Soil Sci.*, vol. 2016, pp. 1–24, 2016, doi: 10.1155/2016/2707989.

[19] M. M. Tumala, A. Salisu, and Y. B. Nmadu, 'Climate change and fossil fuel prices: A GARCH-MIDAS analysis', *Energy Econ.*, vol. 124, p. 106792, Aug. 2023, doi: 10.1016/j.eneco.2023.106792.

[20] R. K. Sukumaran, L. D. Gottumukkala, K. Rajasree, D. Alex, and A. Pandey, 'Butanol Fuel from Biomass', in *Biofuels*, Elsevier, 2011, pp. 571–586. doi: 10.1016/B978-0-12-385099-7.00026-7.

[21] T. Mahmood, N. Hussain, A. Shahbaz, S. I. Mulla, H. M. N. Iqbal, and M. Bilal, 'Sustainable production of biofuels from the algae-derived biomass', *Bioprocess Biosyst. Eng.*, vol. 46, no. 8, pp. 1077–1097, Aug. 2023, doi: 10.1007/s00449-022-02796-8.

[22] B. Biswas, J. Kumar, and T. Bhaskar, 'Advanced Hydrothermal Liquefaction of Biomass for Bio-Oil Production', in *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels*, Elsevier, 2019, pp. 245–266. doi: 10.1016/B978-0-12-816856-1.00010-5.

[23] C. Birgen, P. Dürre, H. A. Preisig, and A. Wentzel, 'Butanol production from lignocellulosic biomass: revisiting fermentation performance indicators with exploratory data analysis', *Biotechnol. Biofuels*, vol. 12, no. 1, p. 167, Dec. 2019, doi: 10.1186/s13068-019-1508-6.

[24] P. Choudhary *et al.*, 'A review of biochemical and thermochemical energy conversion routes of wastewater grown algal biomass', *Sci. Total Environ.*, vol. 726, p. 137961, Jul. 2020, doi: 10.1016/j.scitotenv.2020.137961.

[25] K. H. Chowdury, N. Nahar, and U. K. Deb, 'The Growth Factors Involved in Microalgae Cultivation for Biofuel Production: A Review', *Comput. Water Energy Environ. Eng.*, vol. 09, no. 04, pp. 185–215, 2020, doi: 10.4236/cweee.2020.94012.

[26] J. Nallasivam, P. F. Prashanth, and R. Vinu, 'Hydrothermal liquefaction of biomass for the generation of value-added products', in *Biomass, Biofuels, Biochemicals*, Elsevier, 2022, pp. 65–107. doi: 10.1016/B978-0-323-88511-9.00018-5.

[27] T. G. Ambaye, M. Vaccari, A. Bonilla-Petriciolet, S. Prasad, E. D. Van Hullebusch, and S. Rtimi, 'Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives', *J. Environ. Manage.*, vol. 290, p. 112627, Jul. 2021, doi: 10.1016/j.jenvman.2021.112627.

[28] D. Palande, N. Ghuge, and R. Shrivastwa, 'Comprehensive Review Of Karanja And Jatropha Biodiesel Fuelled Diesel Engines', *Transdiscipl. J. Eng. Sci.*, vol. 13, Aug. 2022, doi: 10.22545/2022/00201.

[29] K. Sandesh and P. Ujwal, 'Trends and perspectives of liquid biofuel – Process and industrial viability', *Energy Convers. Manag. X*, vol. 10, p. 100075, Jun. 2021, doi: 10.1016/j.ecmx.2020.100075.

[30] M. J. Shahbazi and M. R. Rahimpour, 'Bioenergy Programs in Australia', in *Encyclopedia of Renewable Energy, Sustainability and the Environment*, Elsevier, 2024, pp. 915–924. doi: 10.1016/B978-0-323-93940-9.00166-3.

[31] G. M. Mathew *et al.*, 'Recent advances in biodiesel production: Challenges and solutions', *Sci. Total Environ.*, vol. 794, p. 148751, Nov. 2021, doi: 10.1016/j.scitotenv.2021.148751.

[32] S. Mahapatra, D. Kumar, B. Singh, and P. K. Sachan, 'Biofuels and their sources of production: A review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus', *Energy Nexus*, vol. 4, p. 100036, Dec. 2021, doi: 10.1016/j.nexus.2021.100036.

[33] H. K. Jeswani, A. Chilvers, and A. Azapagic, 'Environmental sustainability of biofuels: a review', *Proc. R. Soc. Math. Phys. Eng. Sci.*, vol. 476, no. 2243, p. 20200351, Nov. 2020, doi: 10.1098/rspa.2020.0351.

[34] D. Özçimen, A. T. Koçer, B. İnan, and T. Özer, 'Bioethanol production from microalgae', in *Handbook of Microalgae-Based Processes and Products*, Elsevier, 2020, pp. 373–389. doi: 10.1016/B978-0-12-818536-0.00014-2.

[35] R. Bibi *et al.*, 'Algal bioethanol production technology: A trend towards sustainable development', *Renew. Sustain. Energy Rev.*, vol. 71, pp. 976–985, May 2017, doi: 10.1016/j.rser.2016.12.126.

[36] T. Jarunglumlert, A. Bampenrat, H. Sukkathanyawat, and C. Prommuak, 'Enhanced Energy Recovery from Food Waste by Co-Production of Bioethanol and Biomethane Process', *Fermentation*, vol. 7, no. 4, p. 265, Nov. 2021, doi: 10.3390/fermentation7040265.

[37] D. Vučurović, B. Bajić, V. Vučurović, R. Jevtić-Mučibabić, and S. Dodić, 'Bioethanol Production from Spent Sugar Beet Pulp—Process Modeling and Cost Analysis', *Fermentation*, vol. 8, no. 3, p. 114, Mar. 2022, doi: 10.3390/fermentation8030114.

[38] S. Nanda, F. Pattnaik, B. R. Patra, K. Kang, and A. K. Dalai, 'A Review of Liquid and Gaseous Biofuels from Advanced Microbial Fermentation Processes', *Fermentation*, vol. 9, no. 9, p. 813, Sep. 2023, doi: 10.3390/fermentation9090813.

[39] P. Ning *et al.*, 'Recent advances in the valorization of plant biomass', *Biotechnol. Biofuels*, vol. 14, no. 1, p. 102, Dec. 2021, doi: 10.1186/s13068-021-01949-3.

[40] M. Kumar, Y. Sun, R. Rathour, A. Pandey, I. S. Thakur, and D. C. W. Tsang, 'Algae as potential feedstock for the production of biofuels and value-added products: Opportunities and challenges', *Sci. Total Environ.*, vol. 716, p. 137116, May 2020, doi: 10.1016/j.scitotenv.2020.137116.

[41] S. G. Arhin, A. Cesaro, F. Di Capua, and G. Esposito, 'Recent progress and challenges in biotechnological valorization of lignocellulosic materials: Towards sustainable biofuels and platform chemicals synthesis', *Sci. Total Environ.*, vol. 857, p. 159333, Jan. 2023, doi: 10.1016/j.scitotenv.2022.159333.

[42] S. K Ghosh, 'Fossil Fuel Consumption Trend and Global Warming Scenario: Energy Overview', *Glob. J. Eng. Sci.*, vol. 5, no. 2, Apr. 2020, doi: 10.33552/GJES.2020.05.000606.

[43] V. Ashokkumar *et al.*, 'Recent advances in lignocellulosic biomass for biofuels and value-added bioproducts - A critical review', *Bioresour. Technol.*, vol. 344, p. 126195, Jan. 2022, doi: 10.1016/j.biortech.2021.126195.

[44] F. Saladini, N. Patrizi, F. M. Pulselli, N. Marchettini, and S. Bastianoni, 'Guidelines for emergy evaluation of first, second and third generation biofuels', *Renew. Sustain. Energy Rev.*, vol. 66, pp. 221–227, Dec. 2016, doi: 10.1016/j.rser.2016.07.073.

[45] C.-Y. Lin and C. Lu, 'Development perspectives of promising lignocellulose feedstocks for production of advanced generation biofuels: A review', *Renew. Sustain. Energy Rev.*, vol. 136, p. 110445, Feb. 2021, doi: 10.1016/j.rser.2020.110445.

[46] N. Hajilary, M. Rezakazemi, and S. Shirazian, 'Biofuel types and membrane separation', *Environ. Chem. Lett.*, vol. 17, no. 1, pp. 1–18, Mar. 2019, doi: 10.1007/s10311-018-0777-9.

[47] H. A. Alalwan, A. H. Alminshid, and H. A. S. Aljaafari, 'Promising evolution of biofuel generations. Subject review', *Renew. Energy Focus*, vol. 28, pp. 127–139, Mar. 2019, doi: 10.1016/j.ref.2018.12.006.

[48] H. K. Jeswani, A. Chilvers, and A. Azapagic, 'Environmental sustainability of biofuels: a review', *Proc. R. Soc. Math. Phys. Eng. Sci.*, vol. 476, no. 2243, p. 20200351, Nov. 2020, doi: 10.1098/rspa.2020.0351.

[49] M. H. Naveed *et al.*, 'Cellulosic biomass fermentation for biofuel production: Review of artificial intelligence approaches', *Renew. Sustain. Energy Rev.*, vol. 189, p. 113906, Jan. 2024, doi: 10.1016/j.rser.2023.113906.

[50] D. Singh, D. Sharma, S. L. Soni, S. Sharma, P. Kumar Sharma, and A. Jhalani, 'A review on feedstocks, production processes, and yield for different generations of biodiesel', *Fuel*, vol. 262, p. 116553, Feb. 2020, doi: 10.1016/j.fuel.2019.116553.

[51] T. G. Ambaye, M. Vaccari, A. Bonilla-Petriciolet, S. Prasad, E. D. Van Hullebusch, and S. Rtimi, 'Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives', *J. Environ. Manage.*, vol. 290, p. 112627, Jul. 2021, doi: 10.1016/j.jenvman.2021.112627.

[52] M. Ebadian, S. Van Dyk, J. D. McMillan, and J. Saddler, 'Biofuels policies that have encouraged their production and use: An international perspective', *Energy Policy*, vol. 147, p. 111906, Dec. 2020, doi: 10.1016/j.enpol.2020.111906.

[53] A. Priya *et al.*, 'Introduction: An overview of biofuels and production technologies', in *Handbook of Biofuels Production*, Elsevier, 2023, pp. 3–24. doi: 10.1016/B978-0-323-91193-1.00002-0.

[54] S. A. Aransiola, M. O. Victor-Ekwebelem, S. S. Leh-Togi Zobeashia, and N. R. Maddela, 'Sources and techniques for biofuel generation', in *Green Approach to Alternative Fuel for a Sustainable Future*, Elsevier, 2023, pp. 311–323. doi: 10.1016/B978-0-12-824318-3.00026-6.

[55] R. A. Usmani, 'Biofuel consumption and global climate change: Solutions and challenges', in *Environmental Sustainability of Biofuels*, Elsevier, 2023, pp. 183–200. doi: 10.1016/B978-0-323-91159-7.00019-9.

[56] F. Martins, C. Felgueiras, M. Smitkova, and N. Caetano, 'Analysis of Fossil Fuel Energy Consumption and Environmental Impacts in European Countries', *Energies*, vol. 12, no. 6, p. 964, Mar. 2019, doi: 10.3390/en12060964.

[57] V. Karthik, S. Periyasamy, V. Varalakshmi, J. M. N. Pauline, and R. Suganya, 'Biofuel: A prime eco-innovation for sustainability', in *Environmental Sustainability of Biofuels*, Elsevier, 2023, pp. 267–284. doi: 10.1016/B978-0-323-91159-7.00006-0.

[58] R. A. Usmani, 'Biofuel consumption and global climate change: Solutions and challenges', in *Environmental Sustainability of Biofuels*, Elsevier, 2023, pp. 183–200. doi: 10.1016/B978-0-323-91159-7.00019-9.

[59] H. Shukla-Pandya, 'Bioenergy as a global public tool and technology transfer', in *Microbial Biotechnology for Bioenergy*, Elsevier, 2024, pp. 263–275. doi: 10.1016/B978-0-443-14112-6.00013-4.

[60] H. Shahbeik *et al.*, 'Biomass to biofuels using hydrothermal liquefaction: A comprehensive review', *Renew. Sustain. Energy Rev.*, vol. 189, p. 113976, Jan. 2024, doi: 10.1016/j.rser.2023.113976.

[61] R. Shobana, S. Vijayalakshmi, B. Deepanraj, and J. Ranjitha, 'Biodiesel production from Capparis spinosa L seed oil using calcium oxide as a heterogeneous catalyst derived from oyster shell', *Mater. Today Proc.*, vol. 80, pp. 3216–3220, 2023, doi: 10.1016/j.matpr.2021.07.215.

[62] S. M. Z. Hossain, 'Biochemical Conversion of Microalgae Biomass into Biofuel', *Chem. Eng. Technol.*, vol. 42, no. 12, pp. 2594–2607, Dec. 2019, doi: 10.1002/ceat.201800605.

[63] M. C. Ndukwu and C. I. Onyeoziri, 'African oil bean seed as feedstock for bio-oil and biodiesel production and on the effects of thermal pre-treatments on the quality of the bio-oil', *Biomass Convers. Biorefinery*, vol. 12, no. 7, pp. 2799–2810, Jul. 2022, doi: 10.1007/s13399-020-00754-6.

[64] S. J. Malode, K. K. Prabhu, R. J. Mascarenhas, N. P. Shetti, and T. M. Aminabhavi, 'Recent advances and viability in biofuel production', *Energy Convers. Manag. X*, vol. 10, p. 100070, Jun. 2021, doi: 10.1016/j.ecmx.2020.100070.

[65] P. M. V. Subbarao, T. C. D' Silva, K. Adlak, S. Kumar, R. Chandra, and V. K. Vijay, 'Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy', *Environ. Res.*, vol. 234, p. 116286, Oct. 2023, doi: 10.1016/j.envres.2023.116286.

[66] R. Palos, A. Gutiérrez, F. J. Vela, M. Olazar, J. M. Arandes, and J. Bilbao, 'Waste Refinery: The Valorization of Waste Plastics and End-of-Life Tires in Refinery Units. A Review', *Energy Fuels*, vol. 35, no. 5, pp. 3529–3557, Mar. 2021, doi: 10.1021/acs.energyfuels.0c03918.

[67] S. Y. Lee *et al.*, 'Waste to bioenergy: a review on the recent conversion technologies', *BMC Energy*, vol. 1, no. 1, p. 4, Dec. 2019, doi: 10.1186/s42500-019-0004-7.

[68] H. A. López-Aguilar, D. Quiroz-Cardoza, and A. Pérez-Hernández, 'Volatile Compounds of Algal Biomass Pyrolysis', *J. Mar. Sci. Eng.*, vol. 10, no. 7, p. 928, Jul. 2022, doi: 10.3390/jmse10070928.

[69] J. Haydary, P. Šuhaj, and J. Husár, 'Waste biomass to methanol–optimisation of gasification agent to feed ratio', *Biomass Convers. Biorefinery*, vol. 11, no. 2, pp. 419–428, Apr. 2021, doi: 10.1007/s13399-020-00692-3.

[70] A. Kryeziu, V. Slovák, and A. Parchaňská, 'Liquefaction of Cellulose for Production of Advanced Porous Carbon Materials', *Polymers*, vol. 14, no. 8, p. 1621, Apr. 2022, doi: 10.3390/polym14081621.

[71] H. Jahangiri, A. A. Lappas, M. Ouadi, and E. Heracleous, 'Production of biofuels via Fischer-Tropsch synthesis: Biomass-to-liquids', in *Handbook of Biofuels Production*, Elsevier, 2023, pp. 449–509. doi: 10.1016/B978-0-323-91193-1.00013-5.

[72] S. Anto *et al.*, 'Algae as green energy reserve: Technological outlook on biofuel production', *Chemosphere*, vol. 242, p. 125079, Mar. 2020, doi: 10.1016/j.chemosphere.2019.125079.

[73] G. R. Mong *et al.*, 'Microwave pyrolysis for valorisation of horse manure biowaste', *Energy Convers. Manag.*, vol. 220, p. 113074, Sep. 2020, doi: 10.1016/j.enconman.2020.113074.

[74] 2024 IEA, 'https://www.iea.org/energy-system/renewables/bioenergy'. [Online]. Available: https://www.iea.org/energy-system/renewables/bioenergy

[75] 2023 STATISTA, 'https://www.statista.com/statistics/243887/biofuel-production-in-leading-countries/'. [Online]. Available: https://www.statista.com/statistics/243887/biofuel-production-in-leading-countries/

[76] 2024 STATISTA, 'https://www.statista.com/statistics/274163/global-biofuel-production-in-oil-equivalent/'. [Online]. Available: https://www.statista.com/statistics/274163/global-biofuel-production-in-oil-equivalent/

[77] M. Ebadian, S. Van Dyk, J. D. McMillan, and J. Saddler, 'Biofuels policies that have encouraged their production and use: An international perspective', *Energy Policy*, vol. 147, p. 111906, Dec. 2020, doi: 10.1016/j.enpol.2020.111906.

[78] M. A. H. Khan *et al.*, 'Investigation of Biofuel as a Potential Renewable Energy Source', *Atmosphere*, vol. 12, no. 10, p. 1289, Oct. 2021, doi: 10.3390/atmos12101289.

[79] I. Dafnomilis, R. Hoefnagels, Y. W. Pratama, D. L. Schott, G. Lodewijks, and M. Junginger, 'Review of solid and liquid biofuel demand and supply in Northwest Europe towards 2030 – A comparison of national and regional projections', *Renew. Sustain. Energy Rev.*, vol. 78, pp. 31–45, Oct. 2017, doi: 10.1016/j.rser.2017.04.108.

[80] 2022 IEA, 'https://www.iea.org/reports/world-energy-outlook-2022'. IEA, 2022.

[81] K. Laçın, B. Çaloğlu, and B. Binay, 'Anaerobic digestion methods for the production of fuels', in *Bioenergy Engineering*, Elsevier, 2023, pp. 201–235. doi: 10.1016/B978-0-323-98363-1.00004-1.

[82] 2024 STATISTA, 'https://www.statista.com/statistics/243942/worldwide-consumption-of-biofuels/'. [Online]. Available: https://www.statista.com/statistics/243942/worldwide-consumption-of-biofuels/

[83] O. M. Adeniyi, U. Azimov, and A. Burluka, 'Algae biofuel: Current status and future applications', *Renew. Sustain. Energy Rev.*, vol. 90, pp. 316–335, Jul. 2018, doi: 10.1016/j.rser.2018.03.067.

[84] L. Cherwoo *et al.*, 'Biofuels an alternative to traditional fossil fuels: A comprehensive review', *Sustain. Energy Technol. Assess.*, vol. 60, p. 103503, Dec. 2023, doi: 10.1016/j.seta.2023.103503.

[85] H. B. Sharma and B. K. Dubey, 'Co-hydrothermal carbonization of food waste with yard waste for solid biofuel production: Hydrochar characterization and its pelletization', *Waste Manag.*, vol. 118, pp. 521–533, Dec. 2020, doi: 10.1016/j.wasman.2020.09.009.

[86] S. Hafeez, S. M. Al-Salem, G. Manos, and A. Constantinou, 'Fuel production using membrane reactors: a review', *Environ. Chem. Lett.*, vol. 18, no. 5, pp. 1477–1490, Sep. 2020, doi: 10.1007/s10311-020-01024-7.

[87] H. Pan *et al.*, 'Recent advances in biodiesel production using functional carbon materials as acid/base catalysts', *Fuel Process. Technol.*, vol. 237, p. 107421, Dec. 2022, doi: 10.1016/j.fuproc.2022.107421.

[88] N. S. Hassan, A. A. Jalil, C. N. C. Hitam, D. V. N. Vo, and W. Nabgan, 'Biofuels and renewable chemicals production by catalytic pyrolysis of cellulose: a review', *Environ. Chem. Lett.*, vol. 18, no. 5, pp. 1625–1648, Sep. 2020, doi: 10.1007/s10311-020-01040-7.

[89] S.-Y. No, 'Production of Liquid Biofuels from Biomass', in *Application of Liquid Biofuels to Internal Combustion Engines*, in Green Energy and Technology. , Singapore: Springer Singapore, 2019, pp. 1–33. doi: 10.1007/978-981-13-6737-3_1.

[90] F. Dalena, A. Senatore, M. Basile, D. Marino, and A. Basile, 'From sugars to ethanol—from agricultural wastes to algal sources: An overview', in *Second and Third Generation of Feedstocks*, Elsevier, 2019, pp. 3–34. doi: 10.1016/B978-0-12-815162-4.00001-X.

[91] T. Mizik and G. Gyarmati, 'Economic and Sustainability of Biodiesel Production—A Systematic Literature Review', *Clean Technol.*, vol. 3, no. 1, pp. 19–36, Jan. 2021, doi: 10.3390/cleantechnol3010002.

[92] U. Rajak and T. N. Verma, 'Effect of emission from ethylic biodiesel of edible and non-edible vegetable oil, animal fats, waste oil and alcohol in CI engine', *Energy Convers. Manag.*, vol. 166, pp. 704–718, Jun. 2018, doi: 10.1016/j.enconman.2018.04.070.

[93] S. Prasad, A. Singh, N. E. Korres, D. Rathore, S. Sevda, and D. Pant, 'Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective', *Bioresour. Technol.*, vol. 303, p. 122964, May 2020, doi: 10.1016/j.biortech.2020.122964.

[94] A. Sharma *et al.*, 'Economic and environmental impacts of biofuels in Indian context', *Mater. Today Proc.*, p. S2214785323027426, May 2023, doi: 10.1016/j.matpr.2023.05.118.

[95] M. S. Habib, M. Tayyab, S. Zahoor, and B. Sarkar, 'Management of animal fat-based biodiesel supply chain under the paradigm of sustainability', *Energy Convers. Manag.*, vol. 225, p. 113345, Dec. 2020, doi: 10.1016/j.enconman.2020.113345.

[96] U. De Corato and E. Viola, 'Biofuel co-products for livestock feed', in *Agricultural Bioeconomy*, Elsevier, 2023, pp. 245–286. doi: 10.1016/B978-0-323-90569-5.00010-X.

[97] C. T. Chong *et al.*, 'Biodiesel sustainability: The global impact of potential biodiesel production on the energy–water–food (EWF) nexus', *Environ. Technol. Innov.*, vol. 22, p. 101408, May 2021, doi: 10.1016/j.eti.2021.101408.

[98] S. Y. Cheng *et al.*, 'Incorporating biowaste into circular bioeconomy: A critical review of current trend and scaling up feasibility', *Environ. Technol. Innov.*, vol. 19, p. 101034, Aug. 2020, doi: 10.1016/j.eti.2020.101034.

[99] A. Kumar, 'Climate Change: Challenges to Reduce Global Warming and Role of Biofuels', in *Climate Change, Photosynthesis and Advanced Biofuels*, A. Kumar, Y.-Y. Yau, S. Ogita, and R. Scheibe, Eds., Singapore: Springer Singapore, 2020, pp. 13–54. doi: 10.1007/978-981-15-5228-1_2.

[100] N. Voca and B. Ribic, 'Biofuel production and utilization through smart and sustainable biowaste management', *J. Clean. Prod.*, vol. 259, p. 120742, Jun. 2020, doi: 10.1016/j.jclepro.2020.120742.

[101] A. N. Larcombe, A. Kicic, B. J. Mullins, and G. Knothe, 'Biodiesel exhaust: The need for a systematic approach to health effects research', *Respirology*, vol. 20, no. 7, pp. 1034–1045, Oct. 2015, doi: 10.1111/resp.12587.

[102] C. Aracil, P. Haro, J. Giuntoli, and P. Ollero, 'Proving the climate benefit in the production of biofuels from municipal solid waste refuse in Europe', *J. Clean. Prod.*, vol. 142, pp. 2887–2900, Jan. 2017, doi: 10.1016/j.jclepro.2016.10.181.

[103] S. Consonni and F. Viganò, 'Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies', *Waste Manag.*, vol. 32, no. 4, pp. 653–666, Apr. 2012, doi: 10.1016/j.wasman.2011.12.019.

[104] D. F. Correa *et al.*, 'Towards the implementation of sustainable biofuel production systems', *Renew. Sustain. Energy Rev.*, vol. 107, pp. 250–263, Jun. 2019, doi: 10.1016/j.rser.2019.03.005.

[105] T. Mizik and G. Gyarmati, 'Economic and Sustainability of Biodiesel Production—A Systematic Literature Review', *Clean Technol.*, vol. 3, no. 1, pp. 19–36, Jan. 2021, doi: 10.3390/cleantechnol3010002.

[106] A. Callegari, S. Bolognesi, D. Cecconet, and A. G. Capodaglio, 'Production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the-art review', *Crit. Rev. Environ. Sci. Technol.*, vol. 50, no. 4, pp. 384–436, Feb. 2020, doi: 10.1080/10643389.2019.1629801.

[107] Y. Subramaniam, T. A. Masron, and N. H. N. Azman, 'Biofuels, environmental sustainability, and food security: A review of 51 countries', *Energy Res. Soc. Sci.*, vol. 68, p. 101549, Oct. 2020, doi: 10.1016/j.erss.2020.101549.

[108] Z. Usmani *et al.*, 'Advancement in valorization technologies to improve utilization of bio-based waste in bioeconomy context', *Renew. Sustain. Energy Rev.*, vol. 131, p. 109965, Oct. 2020, doi: 10.1016/j.rser.2020.109965.

[109] R. C. Rial, 'Biofuels versus climate change: Exploring potentials and challenges in the energy transition', *Renew. Sustain. Energy Rev.*, vol. 196, p. 114369, May 2024, doi: 10.1016/j.rser.2024.114369.

[110] Z. Usmani *et al.*, 'Lignocellulosic biorefineries: The current state of challenges and strategies for efficient commercialization', *Renew. Sustain. Energy Rev.*, vol. 148, p. 111258, Sep. 2021, doi: 10.1016/j.rser.2021.111258.

[111] Y. Guo *et al.*, 'Production of butanol from lignocellulosic biomass: recent advances, challenges, and prospects', *RSC Adv.*, vol. 12, no. 29, pp. 18848–18863, 2022, doi: 10.1039/D1RA09396G.

[112] M. Aghbashlo, M. Tabatabaei, S. Soltanian, H. Ghanavati, and A. Dadak, 'Comprehensive exergoeconomic analysis of a municipal solid waste digestion plant equipped with a biogas genset', *Waste Manag.*, vol. 87, pp. 485–498, Mar. 2019, doi: 10.1016/j.wasman.2019.02.029.

[113] P. Gabrielli, M. Gazzani, and M. Mazzotti, 'The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry', *Ind. Eng. Chem. Res.*, vol. 59, no. 15, pp. 7033–7045, Apr. 2020, doi: 10.1021/acs.iecr.9b06579.

[114] S. Vickram *et al.*, 'Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management – A critical review', *Bioresour. Technol.*, vol. 387, p. 129660, Nov. 2023, doi: 10.1016/j.biortech.2023.129660.

[115] J. C. López-Linares, M. Coca, P. E. Plaza, S. Lucas, and M. T. García-Cubero, 'Waste-to-fuel technologies for the bioconversion of carrot discards into biobutanol', *Renew. Energy*, vol. 202, pp. 362–369, Jan. 2023, doi: 10.1016/j.renene.2022.11.093.

[116] B. Kumar, N. Bhardwaj, K. Agrawal, V. Chaturvedi, and P. Verma, 'Current perspective on pretreatment technologies using lignocellulosic biomass: An emerging biorefinery concept', *Fuel Process. Technol.*, vol. 199, p. 106244, Mar. 2020, doi: 10.1016/j.fuproc.2019.106244.

[117] N. Srivastava *et al.*, 'Impact of nanomaterials on sustainable pretreatment of lignocellulosic biomass for biofuels production: An advanced approach', *Bioresour. Technol.*, vol. 369, p. 128471, Feb. 2023, doi: 10.1016/j.biortech.2022.128471.

[118] F. Almomani *et al.*, 'Comprehensive insights into conversion of microalgae to feed, food, and biofuels: Current status and key challenges towards implementation of sustainable biorefineries', *Chem. Eng. J.*, vol. 455, p. 140588, Jan. 2023, doi: 10.1016/j.cej.2022.140588.

[119] R. Singh, H. Liu, J. Shanklin, and V. Singh, 'Hydrothermal pretreatment for valorization of genetically engineered bioenergy crop for lipid and cellulosic sugar recovery', *Bioresour. Technol.*, vol. 341, p. 125817, Dec. 2021, doi: 10.1016/j.biortech.2021.125817.

[120] H. Shokravi *et al.*, 'Fourth generation biofuel from genetically modified algal biomass: Challenges and future directions', *Chemosphere*, vol. 285, p. 131535, Dec. 2021, doi: 10.1016/j.chemosphere.2021.131535.

[121] F. Sher, I. Ziani, M. Hameed, S. Ali, and J. Sulejmanović, 'Advanced nanomaterials design and synthesis for accelerating sustainable biofuels production – A review', *Curr. Opin. Green Sustain. Chem.*, vol. 47, p. 100925, Jun. 2024, doi: 10.1016/j.cogsc.2024.100925.

[122] P. Mealy and A. Teytelboym, 'Economic complexity and the green economy', *Res. Policy*, vol. 51, no. 8, p. 103948, Oct. 2022, doi: 10.1016/j.respol.2020.103948.

[123] Y. Ye *et al.*, 'Biofuel production for circular bioeconomy: Present scenario and future scope', *Sci. Total Environ.*, vol. 935, p. 172863, Jul. 2024, doi: 10.1016/j.scitotenv.2024.172863.

[124] D. Lin *et al.*, 'Catalyst Design Strategies for Deoxygenation of Vegetable Oils to Produce Second-Generation Biodiesel', *Ind. Eng. Chem. Res.*, vol. 62, no. 32, pp. 12462–12481, Aug. 2023, doi: 10.1021/acs.iecr.3c01542.