



Article Info

Received: 13th October 2024Revised: 13th December 2024Accepted: 20th January 2025

¹Department of Biochemistry & Molecular Biology, Federal University Dutsinma Katsina State Nigeria

²Department of Biological Sciences, Faculty of Science, Yobe State University, Damaturu, Nigeria

³Ibrahim Shehu Shema Centre for Renewable Energy, Umaru Musa Yar'dua University, PMB 2218, Katsina, Nigeria

*Corresponding author's email:

nlawalbatagarawa@fudutsinma.edu.ng

Cite this: CaJoST, 2025, 1, 108-121

Biofuel: A Sustainable Solution for Energy Supply in the 21st Century

Lawal Nura^{1*}, Karimah M. Rabi² and Jibiya S. Abdulkarim³

Biofuel has emerged as a viable alternative to fossil fuels, addressing the growing need for sustainable energy solutions worldwide. Derived from organic sources like biomass and plant matter, biofuels offer numerous benefits, including reduced greenhouse gas emissions, enhanced energy security and economic gains. This review explores cutting-edge biofuel production technologies and their significance as a sustainable energy source. Biofuels come in various forms, such as biodiesel, bioethanol and biogas, produced through fermentation, gasification and transesterification. Each biofuel type has distinct qualities and applications. However, challenges persist, including resource competition with food production and technological inefficiencies. To overcome these obstacles, innovations and advancements are necessary. Supporting policies and legislation must be implemented to ensure sustainable biofuel production. Collaboration among scientists, policymakers and industry stakeholders is crucial for developing a sustainable biofuel sector. Biofuel technology holds great promise for meeting the 21st century's energy demands while reducing fossil fuel dependence and environmental harm. Further research and innovation are necessary to optimize production processes and fully realize biofuel's potential.

Keywords: Biofuel, fossil fuels, biomass, fermentation, gasification, transesterification.

1. Introduction

Biofuel is a renewable power option that is derived from animal manure and biomass (feedstocks), which includes plant and algae. Fossil fuel depletion, rising fuel costs, increased fuel consumption, and global warming are the factors contributing to the trending research into alternative energy generation possibilities (Jayakumar *et al.*, 2023). Also, the human-caused greenhouse gas (GHG) emissions from fossil fuel production and use, including the release of carbon dioxide (CO₂) have recently elevated the advancement of clean energy sources to a global priority. Unlike traditional energy sources (fossil fuels), it can be created quickly from biomass, which makes it a renewable energy source. Energy for transportation, heating, and power generation are all possible with biofuel (Dick, 2014).

Research on biofuels has progressed significantly since 2000. Biomass uniquely offers solid, liquid, and gaseous fuels. Wood fuels remain steady, while wood chips/pellets for energy have grown 100% and will keep rising (Praveena *et al.*, 2024).

Drop-in transportation fuels, pyrolysis bio-oil, bioethanol, and biodiesel are all considered liquid biofuels. Commercial manufacturing of bioethanol from lignocellulosic compounds has only recently

begun, augmenting the 22 billion gallons produced annually, mostly from agricultural products (Bušić *et al.*, 2018). The production capacity of oil seed biodiesel has reached 5670 million gallons per year, and additional increases are contingent upon the development of new feedstock. Drop-in biofuels and bio-oil are still in the development stage and face difficulties in upgrading and cost-effective conversion (Brahma *et al.*, 2022).

Syngas and biogas are examples of gaseous biofuels. In Europe and China, the anaerobic digestion process of producing biogas from organic matter has been growing quickly. This process has the potential to replace 25% of the natural gas consumption that occurs now. On the other hand, the process of producing syngas by the incineration of wood-based biomass is limited in its application due to its ineffective cost (Guiot and Frigon, 2012).

The rationale for this review is centred on biofuels' potential to mitigate climate change, ensure energy security, and foster sustainable development through reduced emissions, energy diversification, and rural economic empowerment. Biofuels offer a low-carbon alternative to fossil fuels, mitigating greenhouse gas emissions. Diversifying energy

sources reduces dependence on imported fuels, enhancing energy independence. Biofuels support rural economies, promote renewable energy, and create jobs. Recent advancements in biofuel technologies warrant updated analysis.

2. Types of Biofuels

2.1. First generation biofuels

Energy crops like sugarcane, sugar beet, and sorghum, starch-based crops like corn, wheat, and barley, or oil-based crops like rapeseed, sunflower, and canola are used to make first-generation biofuels (Dahman *et al.*, 2019). The fermentation or chemical processes used to create these biofuels transform the oils, sugars, and starches in the biomass into liquid fuels (Cavelius *et al.*, 2023). First-generation biofuels that are most widely used are bioethanol and biodiesel (Hirani *et al.*, 2018). Since different feedstocks can be used to manufacture these biofuels, production can be flexible based on local conditions and resource availability (Martin, 2010). Despite availability and the fact that they have been in use for a while (Nagler and Gerace, 2020) the manufacture of biofuel from food crops can raise issues with food security and raise the question of whether food should be used for fuel or food (Naqvi and Yan, 2015). Also, it has been shown that the potential for first-generation biofuels to reduce overall emissions may be limited since they may emit more greenhouse gases than other generation biofuels (Moodley, 2021). However, first-generation biofuels remain a crucial component of the alternative energy sector.

2.1.1. Bioethanol

The most well-known biofuel is bioethanol, which is generally obtained by fermenting crops like sugarcane, maize, and wheat (Mohapatra *et al.*, 2019). And without requiring engine adjustments, it can be primarily converted to conventional fuel in amounts up to 5% to raise its octane and lower pollutants that cause pollution, such as carbon monoxide (Ibeto *et al.*, 2011). In addition to being far less harmful than fossil fuels, bioethanol is also biodegradable, making it a more environmentally responsible choice (Balat *et al.*, 2008).

2.1.2. Biodiesel

Long-chain fatty acid methyl esters are the main component of biodiesel, a type of fuel oil made from plants or animals. It is usually generated by lipids that react chemically, like lard, soybean oil, or any other vegetable oil, with alcohol and microalgae lipid through the process of transesterification, and it results in the production of methyl, ethyl, or propyl ester (Malabadi *et al.*, 2023). Non-edible feedstocks have emerged as a sustainable biofuel source, leveraging waste land and yielding comparable or

higher outputs than edible counterparts (Devarajan *et al.*, 2022). The energy equilibrium of soybean biodiesel is positive, which indicates that the fuel's energy content exceeds the energy required to create it (Fore *et al.*, 2011). Compared to diesel made from petroleum, biodiesel is less harmful to the environment, safe, and biodegradable. It can be used in its natural state, B100 or blended with petroleum-based diesel. Blends such as B5 and B20, or B2 (2% biodiesel), are widely utilized. Othman *et al.* (2017) observed that most manufacturers are satisfied with mixtures up to B5. A few accept mixes up to B20. Biodiesel has less carbon and more oxygen and hydrogen than conventional fuel. This quality lowers the amount of unburned carbon particles and the rate at which biodiesel burns (Torkashvand *et al.*, 2022).

2.1.3. Biogas

Biogas is generated from waste products such as compost, agricultural litter, plant matter, waste water and food scraps. Anaerobic microbes, also known as methanogens, produce biogas by decomposing biological waste in an oxygen-free atmosphere (Calero *et al.*, 2023). Methane (CH₄) and carbon dioxide (CO₂) make up the majority of the gas composition, with trace amounts of moisture, siloxanes, and hydrogen sulfide (H₂S) possible (Malunga, 2018). The generation of biogas contributes to the decrease in methane emissions that fuel global warming. Additionally, it can lessen the need for waste dumps, which emit the hazardous greenhouse gas methane (Harris, 2014). Biogas's composition can be difficult to control because of its variable methane-to-carbon dioxide ratio. Although the ratio can vary from 45% to 75% methane and 55% to 95% carbon dioxide, the most typical ratio is 60% CH₄ (methane) and 40% CO₂ (Al-Timimi and Yaakob, 2022).

2.2. Second generation biofuels

These biofuels are produced using lignocellulosic biomass a structural substance made primarily of lignin, hemicellulose, and cellulose, which makes up a large portion of plant mass. In order for cellulose to ferment into alcohol, lignin and cellulose in plants are separated. This includes both non-food agricultural residues (like hulls of rice or corn stalks) and non-edible plant biomass (like grasses or trees grown specifically for energy) (Naik *et al.*, 2010). Cellulosic ethanol is the primary form of second-generation biofuel now in use or being developed. It is made by fermenting carbohydrates (Kowalski *et al.*, 2022). The methods for producing them are less refined and more complicated than those for first-generation biofuels (Nagler and Gerace, 2020). The development of biofuels of the second generation is less harmful to the environment than that of the first since it may be used as an efficient waste management tool, diversify sources of energy and reduce dependency on carbon-based fuels

(Kowalski *et al.*, 2022). In line with life-cycle assessments, second-generation biofuels will result in "net energy increases," circumventing one more major drawback of first-generation biofuels (Kumar *et al.*, 2022).

2.2.1. Cellulosic ethanol

A variety of feedstocks, including maize residue, switchgrass, miscanthus, sugarcane bagasse, and other grasses or woody crops, can be used to create cellulosic ethanol, a second-generation biofuel. Since it is capable of being produced from unconsumable plant components and doesn't disrupt the food chain, this form of ethanol is thought to be better for the environment than first-generation biofuels (Kumar *et al.*, 2022). However, the conversion rate, or the quantity of raw materials required to make the same volume of ethanol, is one of the difficulties in producing cellulosic ethanol (Ziolkowska, 2020).

Biochemical and thermochemical processes are the two main techniques used in the synthesis of cellulosic ethanol. The biochemical process includes a preliminary step that involves releasing the hemicellulose carbohydrates. Cellulose and hemicellulose are hydrolyzed by enzymes to yield simple sugars. Sugars are subjected to fermentation to generate water and ethanol, which are further separated by distillation (Guo *et al.*, 2022).

The thermochemical process involves pretreatment to induce swelling of hemicellulose and cellulose. Hemicellulose and cellulose are then hydrolyzed chemically to produce simple sugars followed by fermentation of the sugars into carbon dioxide and ethanol. Then a final distillation process to extract ethanol from water (Lynd *et al.*, 2017).

2.2.2. Algal biofuel

Produced from algae, algal biofuels represent a viable renewable energy source (Gajraj *et al.*, 2018). Due to their quick biomass production and relatively high oil content in the form of triacylglycerol, microalgae have long been considered promising sources for biofuel generation (Ganesan *et al.*, 2020). When compared to conventional crops, microalgae develop extremely quickly. Algal mass production can be carried out on non-arable fields using sewage and non-potable saline water (Adetunji *et al.*, 2023). Growing the algae, collecting the biomass, and extracting the oil, which is subsequently converted into biodiesel are the stages involved in the manufacturing of algal biofuels (Pragya *et al.*, 2013). Currently, the cost of producing algae-based biodiesel prevents its commercialization, though, and there are issues with selecting high lipid-containing algae strains as well as high infrastructure, operation, and maintenance expenses (Saad *et al.*, 2019).

2.2.3. Biohydrogen

A promising sustainable energy source. Numerous biological processes can be used to create biohydrogen (Kumar Gupta *et al.*, 2013). The creation of biohydrogen can be achieved by three main technologies; anaerobic dark fermentation, light and dark fermentation combined, and photosynthetic (Ahmed *et al.*, 2021). The aforementioned techniques use different feedstocks. The production of biohydrogen is confronted with obstacles for instance, poor output and expensive manufacture; nonetheless, research is progressing to enhance its efficiency by adjustments in processes, physiological manipulations, and genetic engineering (Putatunda *et al.*, 2022).

2.3. Third generation biofuels

These are more sophisticated and made from microalgae or algae (Müller *et al.*, 2023). Algal-based biofuel output is approximately ten times higher than that of biofuels made from second-generation algae, making them a more effective source of energy (Neto *et al.*, 2019). Since algae are not consumed by humans or animals, they don't endanger the food chain (Behera *et al.*, 2015). Because algae can absorb carbon dioxide from the atmosphere, they aid in lowering the release of greenhouse gases (Bajpai, 2019). However, due to the significant energy and infrastructural requirements, the generation of biofuels derived from algae is more costly than that of conventional fossil fuels (Lee and Lavoie, 2013). It is also difficult and costly to control the environment for the best growth of algae (Alaswad *et al.*, 2015).

2.3.1. Biobutanol

The 4-carbon alcohol biobutanol is made from an array of feedstocks, such as grain of maize and various biomasses (Liu *et al.*, 2022). Because of its higher energy content and reduced water absorption, it's thought to be a more effective fuel for energy than ethanol (Guo *et al.*, 2022). Better blending ability, less corrosiveness, and compatibility with the current gasoline distribution infrastructure are just a few of the benefits that biobutanol has over ethanol (Radloff *et al.*, 2016). But there are difficulties in producing it, like high production costs, time requirements, and sporulation stage (Liu *et al.*, 2022). The production process involves; feedstock preparation and pretreatment, fermentation process, product recovery and purification. Enhancing the fermentation stage's efficiency, modifying the raw material's pretreatment, creating new substrates, and creating more efficient preparation techniques remain the primary area of study and development for the biobutanol industry. The manipulation of microorganisms, biomass, and the substrate necessary for microbial growth has all been investigated through recombinant DNA technology (García *et al.*, 2011).

2.3.2. BioDME

Bio-dimethyl ether, or BioDME, is a sophisticated biofuel made from biomass. It offers various benefits for the environment and the economy and suitable for usage as a renewable diesel engine fuel (Im-orb and Piroonlerkgul, 2023). It has been demonstrated that BioDME, which is made from lignocellulosic biomass, produces considerably lower greenhouse gas emissions compared to fossil fuels (Parvez *et al.*, 2018). With better, cleaner combustion, it is potentially utilized in a range of vehicles, mainly cars, trucks, trains, and ships to replace diesel fuel (Himabindu and Ravikrishna, 2010). The process of producing BioDME from biomass is very intensive and versatile, possibly substituting a large amount of fossil fuels and lower carbon dioxide emissions (de Jong *et al.*, 2023).

2.3.3. Synthetic Hydrocarbons

Hydrocarbon fuels known as synthetic hydrocarbons (SHCs) are made from sources of biomass through a range of biological and thermochemical methods (Konarova *et al.*, 2022). They can be used as renewable fuel in diesel engines and are regarded as advanced biofuels. Better blending ability, less corrosiveness, and compatibility with the current gasoline distribution infrastructure are a few benefits of SHCs (Willauer and Hardy, 2020).

2.4. Fourth generation biofuels

These are a relatively new idea. Their goal is to provide a means of capturing and storing CO₂ while producing sustainable energy. They are made from genetically engineered microorganisms and feedstocks, such as algae. (Mat Aron *et al.*, 2020). In comparison to earlier generations of biofuels, they are anticipated to be a lot efficient, and they may also be able to lessen harmful emissions and the consequences of global warming (Goria *et al.*, 2022).

2.4.1. Bioelectricity

The electrical currents and potentials produced by or existing within live cells, tissues, and organisms are referred to as bioelectricity. It is involved in a number of biological activities, such as nerve impulses, muscle contractions, and cell communication. Bioelectricity generation, on the other hand, is the process of using bioelectricity as a renewable energy source (Dessie and Tadesse, 2022). Biopower systems use processes including burning, bacterial decomposition, and conversion to gas or liquid fuel to turn sustainable biomass fuels into heat and electricity (Rojas-Flores *et al.*, 2021). Bioelectricity may find use in medical devices and epidermal regeneration (Martinsen and Heiskanen, 2023).

2.4.2. Solar fuels

Solar fuels are synthetic chemical fuels made from sun radiation by a variety of mechanisms, including photochemical, photobiological, and electrochemical reactions (Haussener, 2022). Because they are sustainable and renewable, they are viewed as a possible replacement for conventional fossil fuels (Styring, 2012). Potential solar fuels include ammonia and hydrazine, hydrogen, and alcohols (such methanol and ethanol) (Detz *et al.*, 2018). Solar fuels can be easily stored and transported due to their high energy density. The absence of net-zero carbon emissions is a distinguishing feature of solar fuels over fossil fuels, which renders them ecologically harmless (Armaroli and Balzani, 2016).

3. Production Methods of Biofuels

Nature of feedstock (biomass) and its intended application determine production process that is employed. For instance, crops with high sugar or lipid content can be fermented to produce ethanol, and oilseed crops like sunflower or canola are capable of generating biofuels (Ruan *et al.*, 2019).

3.1. Sugar fermentation

In order to convert biomass into bioenergy, this is the method that is most frequently employed. Using this method, cellulosic feedstocks, sweet sorghum, corn, sugarcane and sugar beet are converted into bioethanol (Li and Khanal, 2016 and Pandey, 2011). First, the biomass is hydrolyzed by an enzyme or an acid to produce sugar, which is subsequently metabolized (fermented) by microorganisms like the yeast, *Saccharomyces cerevisiae* to produce ethanol. The most common fermentation substrate is often 6-carbon sugars (Li and Khanal, 2016). Other microorganisms can also ferment five-carbon sugars that come from plant material, or lignocellulosic biomass (Naveed *et al.*, 2024). The efficiency, temperature requirements, pH range, and substrate specificity of different microorganisms and fermentation processes can differ (Tropea, 2022). In contrast to feedstocks derived from sugar, feedstocks derived from starch necessitate starch hydrolysis, or the liquefaction and saccharification of starch, in order to yield fermentable sugars following milling and mashing (Rodionova *et al.*, 2017).

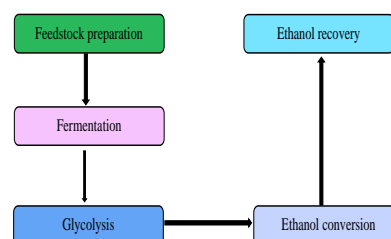


Figure 1. Sugar fermentation process. Integrated from Manmai *et al.* (2020). Illustrated by the authors.

3.2. Hydrolysis

The extraction of sugars from lignocellulosic biomass can be accomplished using a variety of techniques, including enzymatic, chemical, and physical processes. The two most effective techniques among them are enzymatic and chemical hydrolysis (Ruan *et al.*, 2019). Utilizing concentrated mineral acids like HCl and H₂SO₄, chemical hydrolysis can be carried out. More manageable and less dangerous cellulose solvents, including ionic liquids, can also be used for it. Despite being relatively inexpensive, the acid hydrolysis approach's utilization is restricted since using powerful acids has negative environmental effects and low yields (Ho *et al.*, 2014).

Highly specialized cellulase enzymes are often responsible for enzymatic hydrolysis, which results in the production reducing sugars, such as glucose. Enzymatic hydrolysis is typically carried out under milder circumstances than chemical hydrolysis, which uses stronger acids (Binod *et al.*, 2011).

3.3. Digestion

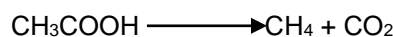
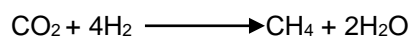
In order to speed up the breakdown of biomass feedstock, biomass digestion uses microorganisms. This process can take place in either anaerobic or aerobic settings. However, anaerobic digestion has a few benefits over aerobic digestion, including increased organic removal efficiency, increased organic loading rate, decreased nutrient requirement and decreased energy requirement (Okoro *et al.*, 2017). In anaerobic digestion, biogas is produced which, depending on the water content, has a methane concentration of roughly 55-75% and a carbon dioxide level of 25%–45%. Additionally, trace gasses like hydrogen sulfide could be created (Champagne, 2008). Specialized bacteria break down complex organic compounds, such as proteins, lipids, and carbohydrates, into smaller molecules, such as soluble sugars, amino acids, and fatty acids, during the anaerobic digestion process. The general reaction is:



Steps involved include (Gould, 2015):

- i. Hydrolysis: Proteins, lipids, carbohydrates, and other big organic polymers are hydrolyzed to produce simpler molecules like fatty acids, amino acids, and simple sugars, and so on.
- ii. Acidogenesis: The process by which acid-producing bacteria and other microbes degrade organic compounds to produce an acidic environment.

- iii. Acetogenesis: Acetate-producing break down a large number of the chemicals generated during acidogenesis into acetic acid, CO₂, and H₂.
- iv. Methanogenesis: The end products of acetogenesis as well as some of the intermediate products of hydrolysis and acidogenesis are converted into methane by methanogens via two main routes.



Methanogenesis requires precise conditions to occur. Physically, it thrives at temperatures of 25-40°C, pH 6.5-8.0, pressures up to 100 atm and redox potentials of -200 to -400 mV. Chemically, it needs nutrients like CO₂, H₂ and acetate, while inhibited by O₂, NO₃⁻ and heavy metals, tolerating freshwater to hypersaline environments. Biologically, methanogenesis involves microorganisms like *Methanobacterium* and *Methanosarcina* in an anaerobic environments (Ferreira *et al.*, 2022). Optimal conditions include temperatures of 35-40°C, pH 7.0-7.5 and redox potentials of -300 to -350 mV. Factors affecting methanogenesis include temperature fluctuations, pH shifts, inhibitor presence, nutrient limitations and microbial community composition (Ghosh and Kar, 2024). Understanding these conditions optimizes methanogenesis in biofuel production (Zakaria and Dhar, 2019).

3.4. Transesterification

Plant biofuels are made of methyl or ethyl esters of long-chain fatty acids. They are often created when alcohols (ethanol or methanol) react with mono, di, and triglycerides (TAGs) or free fatty acids (FAAs) (Barbosa *et al.*, 2022). The process of transesterification transforms triglycerides (fats and oils) into a mixture of fatty acid methyl esters (FAME) in the presence of alcohol, methanol or ethanol and a base catalyst usually potassium hydroxide or sodium hydroxide to produce biodiesel (Baskar *et al.*, 2019; Clifford, 2021). This reaction significantly decreases the viscosity of non-edible oil (Teo *et al.*, 2022). Oil seed that has more than 20% oil content qualifies as an oil feedstock for the synthesis of biodiesel (Li and Khanal, 2016).

3.5. Thermochemical conversion

Thermochemical conversion routes break connections between nearby hydrogen, oxygen, and carbon molecules to release the chemical energy that was generated in the course of photosynthesis. Examples of thermochemical transformation include gasification, liquefaction, pyrolysis, and combustion (Ram and Mondal, 2022). The amount of O₂ changes the process during every step of the thermochemical conversion of biomass. Combustion is the thermochemical process that requires an

excess of oxygen, while pyrolysis is the process that does not require oxygen (Ong *et al.*, 2019).

3.5.1. Gasification

Gasification transforms solid biomass into a combination of gases called synthesis gas (syngas), that consists of carbon dioxide (CO₂), hydrogen (H₂), and carbon monoxide (CO) by employing heat and a gasifying agent. After that, the syngas can be utilized to make biofuels. By using chemical processes like Fischer-Tropsch synthesis, synthesis gases can create fuel and other compounds (Brown, 2019). Reactor design, temperature, gasification agent (steam, oxygen, or air), and feedstock characteristics are some of the variables that affect the complicated process of gasification (Ortiz, 2022). Gasification reactions include:

- i. Partial oxidation: The biomass is partially oxidized when a specific volume of air or oxygen is added to the chamber. In addition to producing heat, this supplies oxygen for the gasification reactions (Lin and Wu, 2019).
- ii. Reduction: Reduction reactions occur when the oxygen in the chamber interacts with the emitted volatile chemicals and char. Tar and other complex hydrocarbons are broken down by these processes, releasing carbon monoxide (CO) and hydrogen (H₂) (Singh *et al.*, 2022).
- iii. Water-gas shift reaction: In addition to carbon dioxide (CO₂), the syngas generated in the preceding phase also contains H₂ and CO. Steam is added to the water-gas shift process so that it can react with the carbon monoxide (CO) and produce more hydrogen (H₂) and carbon dioxide (CO₂). The syngas's composition can be adjusted with the aid of this shift reaction (Tanger *et al.*, 2013).

3.5.2. Hydrothermal liquefaction (HTL)

This process turns biomass into biofuels in the presence of water while operating at high temperatures (200–400°C) and pressures (10–25 MPa) (Zhang and Chen, 2018). Alkali salts like potassium and sodium carbonate can work as a catalyst to break down macromolecules like cellulose and hemicellulose into tiny fragments. The thick heavy oil that is produced during the liquefaction process can occasionally be difficult to handle. Propanol, methyl ethyl ketone, butanol, acetone, ethyl acetate, and other organic solvents are introduced to the reaction system to loosen it (Ruan *et al.*, 2019). Volatile organic acids, alcohols, aldehydes, ethers, esters, ketones, and nonvolatile components are typically found in high concentrations in biofuels that are produced during

the liquefaction process. Components might be enhanced chemically to create an organic distillate product that is abundant in valuable compounds and hydrocarbons (Yu *et al.*, 2023).

3.5.3. Pyrolysis

This method uses heat in the absence of oxygen to turn biomass into biofuels (Su *et al.*, 2022). Traditional electrical pyrolysis is categorized into three groups depending on the operating features include residence time, pyrolysis temperature, and heating rate. These three types of pyrolysis are flash, rapid, and slow (Ruan *et al.*, 2019). Fast pyrolysis, which involves rapidly heating biomass to a high temperature in the absence of oxygen, produces, depending on the feedstock used, 60%–75% oily products (oil and other liquids), 15%–25% solids (largely charcoal), and 10%–20% gaseous phase. (Jahirul *et al.*, 2012). In pyrolysis, the biomass feedstock reacts as follows overall:

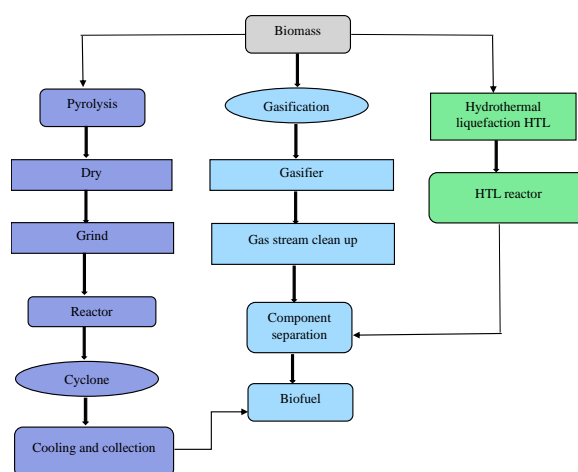


Figure 2. Thermochemical conversion process including pyrolysis, gasification and hydrothermal liquefaction. Integrated from Ram and Mondal (2022). Illustrated by the authors.

3.6. Electrofuel production

Utilizing microorganisms to produce liquid transportation fuels devoid of photosynthesis is known as electrofuel production. These microbes convert carbon dioxide (CO₂) into liquid fuels by using energy from electricity and chemical molecules like hydrogen (Hollinshead *et al.*, 2014).

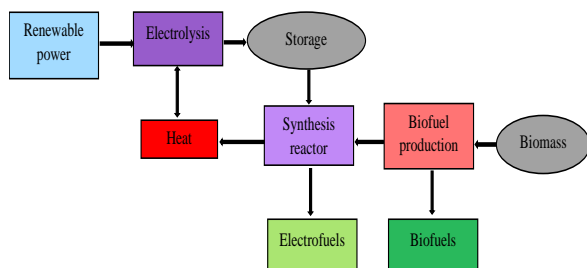


Figure 3. Electrofuel production process. Integrated from Isaacs *et al.* (2021). Illustrated by the authors.

4. Advantages of Biofuel

4.1. Renewable energy source

This is due to the fact that it is composed of organic materials including algae, crops, and plant waste. Unlike fossil fuels, which are scarce and will eventually run out, biofuels are abundant. (Gebremariam and Marchetti, 2018).

4.2. Decreased greenhouse gas emissions

In general, biofuels emit less carbon dioxide (CO₂) than fossil fuels do. This is so because the carbon dioxide those plants take during growth balances out the carbon dioxide that is emitted when biofuels are consumed. Consequently, the total amount of greenhouse gas emissions linked to climate change is decreased by biofuels (Abdulkareem-Alsultan *et al.*, 2020).

4.3. Energy security and independence

A lot of nations rely mostly on imported fossil fuels. Nations can enhance their energy security and independence by lowering their dependency on imported fossil fuels by cultivating biofuels on their own soil (Bento, 2009).

4.4. Employment creation

The cultivation, refining, and marketing of biofuels generate employment in a number of industries, including manufacturing, transportation, and agriculture. This has the potential to lower unemployment rates and boost economic growth (Datta, 2022).

4.5. Environmental benefits

Oil spills and air pollution are two issues surrounding fossil fuel extraction that biofuels may be able to reduce. Since producing biofuel frequently entails growing energy crops on degraded or abandoned land, it can also encourage efforts at land rehabilitation and reforestation (Zhang, 2011).

4.6. Technological advancement

The development of biofuel technology encourages study and innovation within the realm of sustainable

energy. This may result in breakthroughs and developments in other renewable energy fields, like wind and solar energy (Bauer, 2017).

4.7. Profits for farmers

Growing energy crops and selling them to companies that make biofuel can help farmers make money. This can offer another source of money and diversify their sources of income (Pahl, 2008).

4.8. Infrastructure compatibility

Without requiring significant changes, biofuels can be combined with conventional fuels and utilized in already-built systems. Since the infrastructure and transportation systems now in place may be used, the switch from fossil fuels to biofuels is made easier (Bhaskar *et al.*, 2011).

4.9. Development of rural areas

The production of biofuels can give these areas new economic prospects. In rural locations, investing in infrastructure and biofuel facilities can boost employment and the local economy (Gheewala *et al.*, 2018).

5. Limitations of Biofuels

5.1. Competition from land use

Creating biofuels needs an enormous amount of land, that might put food crops, forests, and natural ecosystems in conflict. In areas where land resources are already few, this may exacerbate deforestation, biodiversity loss, and food shortages (Koh and Ghazoul, 2008).

5.2. Increased water usage

The development of numerous biofuel crops, such corn and sugarcane, necessitates substantial water usage. This could put a burden on water supplies, particularly in places where there is currently a drought or limited water availability (Datta, 2022).

5.3. Energy intensive production

Steps that need a lot of energy are commonly included in the manufacture of biofuels, including conversion, processing, and cultivation. Concerns over overall energy efficiency arise because biofuels typically provide a lower total energy gain than their production energy. (Torkashvand *et al.*, 2022).

5.4. Adverse environmental effects

Although biofuels can lower greenhouse gas emissions, there may be additional environmental problems associated with their production. Clearing land for biofuel crops, for instance, may cause ecosystems to be disrupted and stored carbon to be released. Furthermore, water contamination and biodiversity loss might result from the fertilizer and

pesticide used in the generating biofuels (Bessou *et al.*, 2011).

5.5. Limited availability of feedstocks

If the appetite for biofuels keeps rising, there won't be as much supply of suitable feedstocks available for the manufacture of biofuels. This may result in more competition for available resources and possibly higher feedstock and food crop costs (Dubey *et al.*, 2023).

5.6. Technical difficulties

Producing biofuel frequently calls for sophisticated technologies and processing techniques. Enhancing the productivity and scalability of biofuel manufacturing, which may be a difficult and drawn-out procedure, requires research and development (Ambaye *et al.*, 2021).

5.7. Socioeconomic effects

Communities in the area and indigenous individuals may be affected by alterations in land ownership and usage patterns caused by the emphasis on producing biofuels. Concerns over the loss of small farmers and the consolidation of power in the hands of big businesses might also exist (Aha, and Ayitey, 2017).

5.8. Food security issues

Using food crops to produce biofuels may give rise to food security issues, especially in areas where access to food is already problematic. It is possible that utilizing crops for fuel rather than food may raise food costs and worsen poverty and hunger (Renzaho *et al.*, 2017).

5.9. Complex supply chains

The manufacturing, distribution, and transportation of biofuels entail intricate networks that can be prone to inefficiencies and logistical difficulties. The implementation of biofuels may become less financially viable as a result (Awais *et al.*, 2021).

5.10. Uncertain environmental advantages

Depending on the particular feedstock, production techniques, and total life cycle analysis, biofuels may or may not have different environmental benefits. Some biofuels may not have a substantially less negative environmental impact than fossil fuels, according to some research, especially when indirect emissions and changes in land use are taken into account (Bessou *et al.*, 2011).

6. Current Situation in Developing Countries

Biofuel technologies are experiencing significant growth in developing countries, driven by government policies and investments. Countries like

Brazil, Argentina and Indonesia have implemented biofuel blending requirements, driving demand for advanced biofuels like ethanol and biodiesel produced from sustainable feedstocks, reducing greenhouse gas emissions (Bastos *et al.*, 2021).

In Africa, biofuel technology and usage are advancing, albeit unevenly. South Africa leads the continent in biofuel production, accounting for 65% of Africa's total output, while Nigeria, Egypt, Kenya, and others are notable producers (Leela *et al.*, 2024). Although challenges persist, including the food vs. fuel debate, sustainability concerns, and infrastructure limitations. The African Union's Bioenergy Policy Framework promotes sustainable development. Emerging trends include innovative feedstocks, advanced conversion technologies, and regional cooperation (Dahunsi *et al.*, 2020). Biofuel demand is growing, driven by transport sector needs (Miftah and Mutta, 2024).

Nigeria's biofuel industry expands, driven by government policies and growing energy demands (Ndukwu *et al.*, 2021). Biofuels account for 1% of the energy mix, with ethanol from cassava, sugarcane, and maize, and biodiesel from jatropha, palm oil, and soybeans (Munonye *et al.*, 2023). Despite challenges, opportunities lie in agricultural waste utilization and rural development. The Nigerian National Petroleum Company (NNPC) Limited and private investors target 20% biofuel blending by 2030 (Aderinto, 2023).

Despite obstacles in scalability, cost and sustainability, biofuel technologies offer opportunities for developing countries. Utilizing agricultural waste, enhancing energy security and creating jobs are key benefits (Das and Gundimeda, 2022). Emerging trends include algae-based biofuels and carbon capture. Effective policies, infrastructure investments and capacity building will propel biofuel technologies, increasing energy access, reducing emissions and fostering sustainable development (Oloyede *et al.*, 2024).

7. Conclusion

Biofuels provide a cost-effective and environmentally friendly energy source. They are a long-term energy source because they are renewable resources that can be produced continually. Their effectiveness in lowering greenhouse gas emissions stems from their carbon-neutral or even carbon-negative nature. Additionally, biofuels can promote energy independence and offer chances for waste management. Although there are obstacles to overcome, with careful planning and sustainable methods, biofuels can be used to meet our energy needs while reducing their negative effects on food production and fostering a sustainable future.

Future directions prioritize research, sustainability and scalability. Key areas include efficient conversion technologies, advanced feedstock breeding and integrated biorefineries. Large-scale production, process optimization and stable policies will reduce costs and foster growth. Emerging trends like algal biofuels, synthetic biology and carbon capture will propel biofuel technologies toward commercial viability, ensuring a reliable, low-carbon energy source, enhanced energy security and mitigated climate change through collaboration and infrastructure investments.

Authors' Contributions

Lawal Nura designed and edited the manuscript, Karimah Muhammad Rabi'u and Shamsuddeen Jibiya Abdulkarim drafted the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

Authors acknowledged the library staff of the Federal University Dutsin-Ma.

References

- Abdulkareem-Alsultan, G., Asikin-Mijan, N., Lee, H. V. and Taufiq-Yap, Y. H. (2020). Biofuels: Past, present, future. *Innovations in Sustainable Energy and Cleaner Environment*, 489-504. https://doi.org/10.1007/978-981-13-9012-8_21
- Adetunji, C. O., Oloke, J. K., Dwivedi, N., Ummalyma, S. B., Dwivedi, S., Hefft, D. I. and Adetunji, J. B. (Eds.). (2023). *Next-Generation Algae, Volume 1: Applications in Agriculture, Food and Environment*. John Wiley & Sons. <https://doi.org/10.1002/9781119857839>
- Aderinto, I. (2023). Assessing the financial feasibility of Nigeria's 2030 targets for solar and nuclear power.
- Aha, B. and Ayitey, J. Z. (2017). Biofuels and the hazards of land grabbing: Tenure (in) security and indigenous farmers' investment decisions in Ghana. *Land Use Policy*, 60: 48-59. <https://doi.org/10.1016/j.landusepol.2016.10.012>
- Alaswad, A., Dassisti, M., Prescott, T. and Olabi, A. G. (2015). Technologies and developments of third generation biofuel production. *Renewable and Sustainable Energy Reviews*, 51: 1446-1460. <https://doi.org/10.1016/j.rser.2015.07.058>
- Ahmed, S. F., Rafa, N., Mofijur, M., Badruddin, I. A., Inayat, A., Ali, M. S., ... and Yunus Khan, T. M. (2021). Biohydrogen production from biomass sources: metabolic pathways and economic analysis. *Frontiers in Energy Research*, 9: 753878. <https://doi.org/10.3389/fenrg.2021.753878>
- Al-Timimi, B. A. and Yaakob, Z. (2022). Catalysts for the simultaneous production of syngas and carbon nanofilaments via catalytic decomposition of biogas. *Natural Gas: New Perspectives and Future Developments*, 197.
- Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., van Hullebusch, E. D. and Rtimi, S. (2021). Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives. *Journal of Environmental Management*, 290: 112627. <https://doi.org/10.1016/j.jenvman.2021.112627>
- Armaroli, N. and Balzani, V. (2016). Solar electricity and solar fuels: status and perspectives in the context of the energy transition. *Chemistry—A European Journal*, 22(1): 32-57. <https://doi.org/10.1002/chem.201503580>
- Awais, F., Flodén, J. and Svanberg, M. (2021). Logistic characteristics and requirements of Swedish wood biofuel heating plants. *Renewable and Sustainable Energy Reviews*, 138: 110650. <https://doi.org/10.1016/j.rser.2020.110650>
- Bajpai, P. (2019). *Third Generation Biofuels* (pp. 11-15). Singapore: Springer. <https://doi.org/10.1007/978-981-13-2378-2>
- Balat, M., Balat, H. and Öz, C. (2008). Progress in bioethanol processing. *Progress in energy and combustion science*, 34(5): 551-573. <https://doi.org/10.1016/j.peccs.2007.11.001>
- Barbosa, S. L., Rocha, A. C. P., Nelson, D. L., de Freitas, M. S., Mestre, A. A. F., Klein, S. I., ... and Rios, R. D. F. (2022). Catalytic transformation of triglycerides to biodiesel with SiO₂-SO₃H and quaternary ammonium salts in toluene or DMSO. *Molecules*, 27(3): 953. <https://doi.org/10.3390/molecules27030953>
- Baskar, G., Kalavathy, G., Aiswarya, R. and Selvakumari, I. A. (2019). Advances in bio-oil extraction from nonedible oil seeds and algal biomass. In *Advances in eco-fuels for a sustainable environment* (pp. 187-210). Woodhead Publishing. <https://doi.org/10.1016/B978-0-08-102728-8.00007-3>
- Bastos Lima, M. G. and Bastos Lima, M. G. (2021). Bioeconomy Lessons from Biofuel Policies in Emerging Countries. *The Politics of Bioeconomy and Sustainability: Lessons from Biofuel Governance, Policies and Production Strategies in the Emerging World*, 179-201. https://doi.org/10.1007/978-3-030-66838-9_8
- Bauer, F., Coenen, L., Hansen, T., McCormick, K. and Palgan, Y. V. (2017). Technological innovation systems for biorefineries: a review of the literature. *Biofuels, bioproducts and biorefining*, 11(3): 534-548. <https://doi.org/10.1002/bbb.1767>
- Behera, S., Singh, R., Arora, R., Sharma, N. K., Shukla, M. and Kumar, S. (2015). Scope of algae as third generation biofuels. *Frontiers in bioengineering and biotechnology*, 2: 90. <https://doi.org/10.3389/fbioe.2014.00090>

- Bento, A. M. (2009). Biofuels: Economic and public policy considerations. Cornell University Library's Initiatives in Publishing (CIP).
- Bessou, C., Ferchaud, F., Gabrielle, B. and Mary, B. (2011). Biofuels, greenhouse gases and climate change. *Sustainable Agriculture Volume 2*: 365-468. https://doi.org/10.1007/978-94-007-0394-0_20
- Bhaskar, T., Bhavya, B., Singh, R., Naik, D. V., Kumar, A. and Goyal, H. B. (2011). Thermochemical conversion of biomass to biofuels. In *Biofuels* (pp. 51-77). Academic Press. <https://doi.org/10.1016/B978-0-12-385099-7.00003-6>
- Binod, P., Janu, K. U., Sindhu, R. and Pandey, A. (2011). Hydrolysis of lignocellulosic biomass for bioethanol production. In *Biofuels* (pp. 229-250). Academic Press. <https://doi.org/10.1016/B978-0-12-385099-7.00010-3>
- Brahma, S., Nath, B., Basumatary, B., Das, B., Saikia, P., Patir, K., & Basumatary, S. (2022). Biodiesel production from mixed oils: A sustainable approach towards industrial biofuel production. *Chemical Engineering Journal Advances*, 10: 100284. <https://doi.org/10.1016/j.cej.2022.100284>
- Brown, R. C. (Ed.). (2019). *Thermochemical processing of biomass: conversion into fuels, chemicals and power*. John Wiley & Sons. <https://doi.org/10.1002/9781119417637>
- Bušić, A., Marđetko, N., Kundas, S., Morzak, G., Belskaya, H., Ivančić Šantek, M., ... & Šantek, B. (2018). Bioethanol production from renewable raw materials and its separation and purification: a review. *Food technology and biotechnology*, 56(3): 289-311.
- Calero, M., Godoy, V., Heras, C. G., Lozano, E., Arjandas, S. and Martín-Lara, M. A. (2023). Current state of biogas and biomethane production and its implications for Spain. *Sustainable Energy & Fuels*, 7(15): 3584-3602. <https://doi.org/10.1039/D3SE00419H>
- Cavelius, P., Engelhart-Straub, S., Mehlmer, N., Lercher, J., Awad, D. and Brück, T. (2023). The potential of biofuels from first to fourth generation. *PLoS Biology*, 21(3): e3002063. <https://doi.org/10.1371/journal.pbio.3002063>
- Champagne, P. (2008). Biomass. In *Future Energy* (pp. 151-170). Elsevier. <https://doi.org/10.1016/B978-0-08-054808-1.00009-0>
- Clifford, C. B. (2021). EGEE 439: Alternative fuels from Biomass sources. Lesson 7.2. *Energy Institute, The Pennsylvania State University*.
- Dahman, Y., Syed, K., Begum, S., Roy, P and Mohtasebi, B. (2019). Biofuels: Their characteristics and analysis. In *Biomass, biopolymer-based materials, and bioenergy* (pp. 277-325). Woodhead Publishing. <https://doi.org/10.1016/B978-0-08-102426-3.00014-X>
- Dahunsi, S. O., Fagbiele, O. O. and Yusuf, E. O. (2020). Bioenergy technologies adoption in Africa: a review of past and current status. *Journal of Cleaner Production*, 264: 121683. <https://doi.org/10.1016/j.jclepro.2020.121683>
- Das, P. and Gundimeda, H. (2022). Is biofuel expansion in developing countries reasonable? A review of empirical evidence of food and land use impacts. *Journal of Cleaner Production*, 372: 133501. <https://doi.org/10.1016/j.jclepro.2022.133501>
- Datta, B. (2022). An economic analysis of biofuels: policies, trade, and employment opportunities. In *Handbook of biofuels* (pp. 3-29). Academic Press. <https://doi.org/10.1016/B978-0-12-822810-4.00001-4>
- de Jong, P., Torres, E. A., de Melo, S. A. B. V., Mendes-Santana, D. and Pontes, K. V. (2023). Socio-economic and environmental aspects of bio-LPG and bio-dimethyl ether (Bio-DME) production and usage in developing countries: The case of Brazil. *Cleaner and Circular Bioeconomy*, 6: 100055. <https://doi.org/10.1016/j.clcb.2023.100055>
- Dessie, Y. and Tadesse, S. (2022). Advancements in Bioelectricity Generation Through Nanomaterial-Modified Anode Electrodes in Microbial Fuel Cells. *Frontiers in Nanotechnology*, 4: 876014. <https://doi.org/10.3389/fnano.2022.876014>
- Detz, R. J., Reek, J. N. H. and Van Der Zwaan, B. C. C. (2018). The future of solar fuels: when could they become competitive?. *Energy & Environmental Science*, 11(7): 1653-1669. <https://doi.org/10.1039/C8EE00111A>
- Devarajan, Y., Munuswamy, D. B., Subbiah, G., Vellaiyan, S., Nagappan, B., Varuvel, E. G. and Thangaraja, J. (2022). Inedible oil feedstocks for biodiesel production: A review of production technologies and physicochemical properties. *Sustainable Chemistry and Pharmacy*, 30: 100840. <https://doi.org/10.1016/j.scp.2022.100840>
- Dick, N. A. (2014). Analysis of biofuel potential in Nigeria (Doctoral dissertation, Newcastle University).
- Dubey, S., Singh, P. K., Dandapat, J., Dubey, P. and Yatchi, T. (2023). Ethical Considerations in Biofuel Agriculture: The Ongoing Discourse Between Food And Fuel. *Boletim de Literatura Oral-The Literary Journal*, 10(1): 3359-3365.
- Ferreira Maluf Braga, A. and Zaiat, M. (2022). Fundamentals of biofuel production using anaerobic digestion: metabolic pathways and factors affecting the process. *Renewable Energy Technologies for Energy Efficient Sustainable Development*, 3-21. https://doi.org/10.1007/978-3-030-87633-3_1
- Fore, S. R., Porter, P. and Lazarus, W. (2011). Net energy balance of small-scale on-farm biodiesel

- production from canola and soybean. *Biomass and bioenergy*, 35(5): 2234-2244. <https://doi.org/10.1016/j.biombioe.2011.02.037>
- Gajraj, R. S., Singh, G. P. and Kumar, A. (2018). Third-generation biofuel: algal biofuels as a sustainable energy source. *Biofuels: Greenhouse Gas Mitigation and Global Warming: Next Generation Biofuels and Role of Biotechnology*, 307-325. https://doi.org/10.1007/978-81-322-3763-1_17
- Ganesan, R., Manigandan, S., Samuel, M. S., Shanmuganathan, R., Brindhadevi, K., Chi, N. T. L., ... and Pugazhendhi, A. (2020). A review on prospective production of biofuel from microalgae. *Biotechnology Reports*, 27: e00509. <https://doi.org/10.1016/j.btre.2020.e00509>
- García, V., Pääkilä, J., Ojamo, H., Muurinen, E. and Keiski, R. L. (2011). Challenges in biobutanol production: how to improve the efficiency?. *Renewable and sustainable energy reviews*, 15(2): 964-980. <https://doi.org/10.1016/j.rser.2010.11.008>
- Gebremariam, S. N. and Marchetti, J. M. (2018). Economics of biodiesel production. *Energy Conversion and Management*, 168: 74-84. <https://doi.org/10.1016/j.enconman.2018.05.002>
- Gheewala, S. H., Damen, B. and Shi, X. (2013). Biofuels: economic, environmental and social benefits and costs for developing countries in Asia. *Wiley Interdisciplinary Reviews: Climate Change*, 4(6): 497-511. <https://doi.org/10.1002/wcc.241>
- Ghosh, S. and Kar, D. (2024). Biohythane: a potential biofuel of the future. *Applied Biochemistry and Biotechnology*, 196(5): 2957-2975. <https://doi.org/10.1007/s12010-022-04291-y>
- Goria, K., Kothari, R., Singh, H. M., Singh, A. and Tyagi, V. V. (2022). Biohydrogen: Potential applications, approaches, and hurdles to overcome. In *Handbook of Biofuels* (pp. 399-418). Academic Press. <https://doi.org/10.1016/B978-0-12-822810-4.00020-8>
- Gould, M. C. (2015, January). Bioenergy and anaerobic digestion. In *Bioenergy* (pp. 297-317). Academic Press. <https://doi.org/10.1016/B978-0-12-407909-0.00018-3>
- Guiot, S. R. and Frigon, J. C. (2012). Anaerobic digestion as an effective biofuel production technology. *Microbial technologies in advanced biofuels production*, 143-161. https://doi.org/10.1007/978-1-4614-1208-3_9
- Guo, Y., Liu, G., Ning, Y., Li, X., Hu, S., Zhao, J. and Qu, Y. (2022). Production of cellulosic ethanol and value-added products from corn fiber. *Bioresources and Bioprocessing*, 9(1): 1-18. <https://doi.org/10.1186/s40643-022-00573-9>
- Harris, P. (2014). Biological Biogas. In *Use, Operation and Maintenance of Renewable Energy Systems: Experiences and Future Approaches* (pp. 95-110). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-03224-5_3
- Haussener, S. (2022). Solar fuel processing: Comparative mini-review on research, technology development, and scaling. *Solar Energy*, 246: 294-300. <https://doi.org/10.1016/j.solener.2022.09.019>
- Himabindu, M. and Ravikrishna, R. V. (2010). Potential of bio-DME as a transportation fuel for India. *Journal of Renewable and Sustainable Energy*, 2(5). <https://doi.org/10.1063/1.3489529>
- Hirani, A. H., Javed, N., Asif, M., Basu, S. K. and Kumar, A. (2018). A review on first-and second-generation biofuel productions. *Biofuels: greenhouse gas mitigation and global warming: next generation biofuels and role of biotechnology*, 141-154. https://doi.org/10.1007/978-81-322-3763-1_8
- Ho, D. P., Ngo, H. H. and Guo, W. (2014). A mini review on renewable sources for biofuel. *Bioresource technology*, 169: 742-749. <https://doi.org/10.1016/j.biortech.2014.07.022>
- Hollinshead, W., He, L. and Tang, Y. J. (2014). Biofuel production: an odyssey from metabolic engineering to fermentation scale-up. *Frontiers in microbiology*, 5: 344. <https://doi.org/10.3389/fmicb.2014.00344>
- Ibeto, C. N., Ofoefule, A. U. and Agbo, K. E. (2011). A global overview of biomass potentials for bioethanol production: a renewable alternative fuel. *Trends in Applied Sciences Research*, 6(5): 410. <https://doi.org/10.3923/tasr.2011.410.425>
- Im-orb, K. and Piroonlerkgul, P. (2023). Sustainability analysis of the bio-dimethyl ether (bio-DME) production via integrated biomass gasification and direct DME Synthesis Process. *Renewable Energy*, 208: 324-330. <https://doi.org/10.1016/j.renene.2023.03.092>
- Isaacs, S. A., Staples, M. D., Allroggen, F., Mallapragada, D. S., Falter, C. P. and Barrett, S. R. (2021). Environmental and economic performance of hybrid power-to-liquid and biomass-to-liquid fuel production in the United States. *Environmental science & technology*, 55(12): 8247-8257. <https://doi.org/10.1021/acs.est.0c07674>
- Jahirul, M. I., Rasul, M. G., Chowdhury, A. A. and Ashwath, N. (2012). Biofuels production through biomass pyrolysis—a technological review. *Energies*, 5(12): 4952-5001. <https://doi.org/10.3390/en5124952>
- Jayakumar, M., Gebeyehu, K. B., Abo, L. D., Tadesse, A. W., Vivekanandan, B., Sundramurthy, V. P., ... and Baskar, G. (2023). A comprehensive outlook on topical processing methods for biofuel production and its thermal applications: Current advances, sustainability and challenges. *Fuel*, 349: 128690. <https://doi.org/10.1016/j.fuel.2023.128690>

- Koh, L. P. and Ghazoul, J. (2008). Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities. *Biological conservation*, 141(10): 2450-2460. <https://doi.org/10.1016/j.biocon.2008.08.005>
- Konarova, M., Aslam, W. and Perkins, G. (2022). Fischer-Tropsch synthesis to hydrocarbon biofuels: Present status and challenges involved. *Hydrocarbon Biorefinery*, 77-96. <https://doi.org/10.1016/B978-0-12-823306-1.00006-6>
- Kowalski, Z., Kulczycka, J., Verhé, R., Desender, L., De Clercq, G., Makara, A., ... and Harazin, P. (2022). Second-generation biofuel production from the organic fraction of municipal solid waste. *Frontiers in Energy Research*, 10: 919415. <https://doi.org/10.3389/fenrg.2022.919415>
- Kumar Gupta, S., Kumari, S., Reddy, K. and Bux, F. (2013). Trends in biohydrogen production: major challenges and state-of-the-art developments. *Environmental technology*, 34(13-14): 1653-1670. <https://doi.org/10.1080/09593330.2013.822022>
- Kumar, R., Dhurandhar, R., Chakraborty, S. and Ghosh, A. K. (2022). Downstream process: toward cost/energy effectiveness. In *Handbook of biofuels* (pp. 249-260). Academic Press. <https://doi.org/10.1016/B978-0-12-822810-4.00012-9>
- Lee, R. A. and Lavoie, J. M. (2013). From first-to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Animal Frontiers*, 3(2): 6-11. <https://doi.org/10.2527/af.2013-0010>
- Leela, D., Wening, N., Kusirini, E. and Nur, S. M. (2024, May). Building a bioenergy system towards a circular bioeconomy in Africa. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1338, No. 1, p. 012059). IOP Publishing. <https://doi.org/10.1088/1755-1315/1338/1/012059>
- Li, Y. and Khanal, S. K. (2016). *Bioenergy: principles and applications*. John Wiley & Sons.
- Lin, K. W. and Wu, H. W. (2019). Thermodynamic analysis and experimental study of partial oxidation reforming of biodiesel and hydrotreated vegetable oil for hydrogen-rich syngas production. *Fuel*, 236: 1146-1155. <https://doi.org/10.1016/j.fuel.2018.09.090>
- Liu, Y., Yuan, Y., Ramya, G., Singh, S. M., Chi, N. T. L., Pugazhendhi, A., ... and Mathimani, T. (2022). A review on the promising fuel of the future—Biobutanol; the hindrances and future perspectives. *Fuel*, 327: 125166. <https://doi.org/10.1016/j.fuel.2022.125166>
- Lynd, L. R., Liang, X., Bidy, M. J., Allee, A., Cai, H., Foust, T., ... and Wyman, C. E. (2017). Cellulosic ethanol: status and innovation. *Current opinion in biotechnology*, 45: 202-211. <https://doi.org/10.1016/j.copbio.2017.03.008>
- Malabadi, R. B., Sadiya, M. R., Kolkar, K. P. and Chalannavar, R. K. (2023). Biodiesel production: An updated review of evidence. *International Journal of Biological and Pharmaceutical Sciences Archive*, 6(02): 110-133. <https://doi.org/10.53771/ijbpsa.2023.6.2.0104>
- Malunga, S. P. (2018). *Production of biogas from sugarcane residues* (Doctoral dissertation).
- Manmai, N., Unpaprom, Y., Ponnusamy, V. K. and Ramaraj, R. (2020). Bioethanol production from the comparison between optimization of sorghum stalk and sugarcane leaf for sugar production by chemical pretreatment and enzymatic degradation. *Fuel*, 278: 118262. <https://doi.org/10.1016/j.fuel.2020.118262>
- Martin, M. A. (2010). First generation biofuels compete. *New biotechnology*, 27(5): 596-608. <https://doi.org/10.1016/j.nbt.2010.06.010>
- Martinsen, O. G. and Heiskanen, A. (2023). *Bioimpedance and bioelectricity basics*. Elsevier. <https://doi.org/10.1016/B978-0-12-819107-1.00004-2>
- Mat Aron, N. S., Khoo, K. S., Chew, K. W., Show, P. L., Chen, W. H. and Nguyen, T. H. P. (2020). Sustainability of the four generations of biofuels—a review. *International Journal of Energy Research*, 44(12): 9266-9282. <https://doi.org/10.1002/er.5557>
- Miftah, F. K. and Mutta, D. (2024). Potential markets and policies for sustainable liquid biofuel production with emphasis to Eastern Africa countries: a review. *Energy, Sustainability and Society*, 14(1): 1. <https://doi.org/10.1186/s13705-023-00428-x>
- Mohapatra, S., Ray, R. C. and Ramachandran, S. (2019). Bioethanol from biorenewable feedstocks: technology, economics, and challenges. In *Bioethanol production from food crops* (pp. 3-27). Academic Press. <https://doi.org/10.1016/B978-0-12-813766-6.00001-1>
- Moodley, P. (2021). Sustainable biofuels: opportunities and challenges. *Sustainable Biofuels*, 1-20. <https://doi.org/10.1016/B978-0-12-820297-5.00003-7>
- Müller, C., Scapini, T., Rempel, A., Abaide, E. R., Camargo, A. F., Nazari, M. T., ... and Alves Jr, S. L. (2023). Challenges and opportunities for third-generation ethanol production: a critical review. *Engineering Microbiology*, 3(1): 100056. <https://doi.org/10.1016/j.engmic.2022.100056>
- Munonye, J. O., Osuji, E. E., Nwachukwu, E. U., Okpara, B. O., Agou, G. D., Opaluwa, H. I., ... and Aligbe, J. O. (2023). A Synthesis Review of Biofuel Industry in Nigeria: Between Opportunities and Challenges. *Environment and Ecology Research*, 11(4): 660-675. <https://doi.org/10.13189/eer.2023.110412>
- Nagler, A. M. and Gerace, S. (2020). *First and Second Generation Biofuels: What's the Difference*. University of Wyoming Extension.

- Naik, S. N., Goud, V. V., Rout, P. K. and Dalai, A. K. (2010). Production of first- and second-generation biofuels: a comprehensive review. *Renewable and sustainable energy reviews*, 14(2): 578-597. <https://doi.org/10.1016/j.rser.2009.10.003>
- Naqvi, M. and Yan, J. (2015). First-generation biofuels. *Handbook of clean energy systems*, 1-18. <https://doi.org/10.1002/9781118991978.hces207>
- Naveed, M. H., Khan, M. N. A., Mukarram, M., Naqvi, S. R., Abdullah, A., Haq, Z. U., ... and Al Mohamadi, H. (2024). Cellulosic biomass fermentation for biofuel production: Review of artificial intelligence approaches. *Renewable and Sustainable Energy Reviews*, 189: 113906. <https://doi.org/10.1016/j.rser.2023.113906>
- Ndukwu, M. C., Onwude, D. I., Bennamoun, L., Abam, F. I., Simo-Tagne, M., Horsfall, I. T., and Briggs, T. A. (2021). Nigeria's Energy deficit: The challenges and Eco-friendly approach in reducing the energy gap. *International Journal of Sustainable Engineering*, 14(3): 442-459. <https://doi.org/10.1080/19397038.2020.1842546>
- Neto, J. M., Komesu, A., da Silva Martins, L. H., Gonçalves, V. O., De Oliveira, J. A. R. and Rai, M. (2019). Third generation biofuels: an overview. *Sustainable bioenergy*, 283-298. <https://doi.org/10.1016/B978-0-12-817654-2.00010-1>
- Okoro, O. V., Sun, Z. and Birch, J. (2017). Meat processing waste as a potential feedstock for biochemicals and biofuels—A review of possible conversion technologies. *Journal of cleaner production*, 142: 1583-1608. <https://doi.org/10.1016/j.jclepro.2016.11.141>
- Oloyede, C. T., Itabiyi, O. E., Popoola, O. A., Jekayinfa, S. O., Olaniyan, M. A., Adebayo, A. O., ... and Fattah, I. M. R. (2024). Navigating prospects and challenges for green fuels for achieving economical, environmental and ecological resilience: a scientific review. *Biofuels*, 15(7): 929-941. <https://doi.org/10.1080/17597269.2023.2299090>
- Ong, H. C., Chen, W. H., Farooq, A., Gan, Y. Y., Lee, K. T. and Ashokkumar, V. (2019). Catalytic thermochemical conversion of biomass for biofuel production: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 113: 109266. <https://doi.org/10.1016/j.rser.2019.109266>
- Ortiz, F. G. (2022). Biofuel production from supercritical water gasification of sustainable biomass. *Energy Conversion and Management*: X, 14: 100164. <https://doi.org/10.1016/j.ecmx.2021.100164>
- Othman, M. F., Adam, A., Najafi, G. and Mamat, R. (2017). Green fuel as alternative fuel for diesel engine: A review. *Renewable and Sustainable Energy Reviews*, 80: 694-709. <https://doi.org/10.1016/j.rser.2017.05.140>
- Pahl, G. (2008). *Biodiesel: growing a new energy economy*. Chelsea Green Publishing.
- Pandey, A. (Ed.). (2011). *Biofuels: alternative feedstocks and conversion processes*. Academic Press.
- Parvez, A. M., Wu, T., Li, S., Miles, N. and Mujtaba, I. M. (2018). Bio-DME production based on conventional and CO₂-enhanced gasification of biomass: A comparative study on exergy and environmental impacts. *Biomass and Bioenergy*, 110: 105-113. <https://doi.org/10.1016/j.biombioe.2018.01.016>
- Pragya, N., Pandey, K. K. and Sahoo, P. K. (2013). A review on harvesting, oil extraction and biofuels production technologies from microalgae. *Renewable and sustainable energy reviews*, 24: 159-171. <https://doi.org/10.1016/j.rser.2013.03.034>
- Praveena, V., Martin, L. J., Matijošius, J., Aloui, F., Pugazhendhi, A. and Varuvel, E. G. (2024). A systematic review on biofuel production and utilization from algae and waste feedstocks—a circular economy approach. *Renewable and Sustainable Energy Reviews*, 192: 114178. <https://doi.org/10.1016/j.rser.2023.114178>
- Putatunda, C., Behl, M., Solanki, P., Sharma, S., Bhatia, S. K., Walia, A. and Bhatia, R. K. (2022). Current challenges and future technology in photofermentation-driven biohydrogen production by utilizing algae and bacteria. *International Journal of Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2022.10.042>
- Radloff, G., Du, X. S., Porter, P. and Runge, T. (2016). Wisconsin strategic bioenergy feedstock assessment. *WI Bioenergy Initiative*. Available online at https://energy.wisc.edu/sites/default/files/pdf/WI_Strategic_Biomass_Assessment_WEB.pdf. Accessed, 16.
- Ram, M. and Mondal, M. K. (2022). Biomass gasification: A step toward cleaner fuel and chemicals. In *Biofuels and bioenergy* (pp. 253-276). Elsevier. <https://doi.org/10.1016/B978-0-323-85269-2.00008-3>
- Renzaho, A. M., Kamara, J. K. and Toole, M. (2017). Biofuel production and its impact on food security in low- and middle-income countries: Implications for the post-2015 sustainable development goals. *Renewable and Sustainable Energy Reviews*, 78: 503-516. <https://doi.org/10.1016/j.rser.2017.04.072>
- Rodionova, M. V., Poudyal, R. S., Tiwari, I., Voloshin, R. A., Zharmukhamedov, S. K., Nam, H. G., ... and Allakhverdiev, S. I. (2017). Biofuel production: challenges and opportunities. *International Journal of Hydrogen Energy*, 42(12): 8450-8461. <https://doi.org/10.1016/j.ijhydene.2016.11.125>
- Rojas-Flores, S., Benites, S. M., De La Cruz-Noriega, M., Cabanillas-Chirinos, L., Valdiviezo-Dominguez, F., Quezada Álvarez, M. A., ... and Angelats-Silva, L. (2021). Bioelectricity

- production from blueberry waste. *Processes*, 9(8): 1301. <https://doi.org/10.3390/pr9081301>
- Ruan, R., Zhang, Y., Chen, P., Liu, S., Fan, L., Zhou, N., ... and Li, B. (2019). Biofuels: introduction. In *Biofuels: Alternative feedstocks and conversion processes for the production of liquid and gaseous biofuels* (pp. 3-43). Academic Press. <https://doi.org/10.1016/B978-0-12-816856-1.00001-4>
- Saad, M. G., Dosoky, N. S., Zoromba, M. S. and Shafik, H. M. (2019). Algal biofuels: current status and key challenges. *Energies*, 12(10): 1920. <https://doi.org/10.3390/en12101920>
- Singh, A. R., Singh, S. K. and Jain, S. (2022). A review on bioenergy and biofuel production. *Materials today: proceedings*, 49: 510-516. <https://doi.org/10.1016/j.matpr.2021.03.212>
- Styring, S. (2012). Solar fuels: vision and concepts. *Ambio*, 41(Suppl 2): 156-162. <https://doi.org/10.1007/s13280-012-0273-6>
- Su, G., Ong, H. C., Mofijur, M., Mahlia, T. I. and Ok, Y. S. (2022). Pyrolysis of waste oils for the production of biofuels: A critical review. *Journal of hazardous materials*, 424: 127396. <https://doi.org/10.1016/j.jhazmat.2021.127396>
- Tanger, P., Field, J. L., Jahn, C. E., DeFoort, M. W. and Leach, J. E. (2013). Biomass for thermochemical conversion: targets and challenges. *Frontiers in plant science*, 4: 218. <https://doi.org/10.3389/fpls.2013.00218>
- Teo, S. H., Islam, A., Mansir, N., Shamsuddin, M. R., Joseph, C. G., Goto, M. and Taufiq-Yap, Y. H. (2022). Sustainable biofuel production approach: Critical methanol green transesterification by efficient and stable heterogeneous catalyst. *Renewable and Sustainable Energy Reviews*, 169: 112889. <https://doi.org/10.1016/j.rser.2022.112889>
- Torkashvand, M., Hasan-Zadeh, A. and Torkashvand, A. (2022). Mini Review on Importance, Application, Advantages and Disadvantages of Biofuels. *J. Mater. Environ. Sci*, 2022(6).
- Tropea, A. (2022). Biofuels Production and Processing Technology. *Fermentation*, 8(7): 319. <https://doi.org/10.3390/books978-3-0365-4823-4>
- Willauer, H. D. and Hardy, D. R. (2020). Synthetic Fuel Development. In *Future Energy* (pp. 561-580). Elsevier. <https://doi.org/10.1016/B978-0-08-102886-5.00026-8>
- Yu, D., Guo, J., Meng, J. and Sun, T. (2023). Biofuel production by hydro-thermal liquefaction of municipal solid waste: Process characterization and optimization. *Chemosphere*, 328: 138606. <https://doi.org/10.1016/j.chemosphere.2023.138606>
- Zakaria, B. S. and Dhar, B. R. (2019). Progress towards catalyzing electro-methanogenesis in anaerobic digestion process: Fundamentals, process optimization, design and scale-up considerations. *Bioresour technol*, 289: 121738. <https://doi.org/10.1016/j.biortech.2019.121738>
- Zhang, Y. H. P. (2011). What is vital (and not vital) to advance economically-competitive biofuels production. *Process Biochemistry*, 46(11): 2091-2110. <https://doi.org/10.1016/j.procbio.2011.08.005>
- Zhang, Y. and Chen, W. T. (2018). Hydrothermal liquefaction of protein-containing feedstocks. In *Direct Thermochemical Liquefaction for Energy Applications* (pp. 127-168). Woodhead Publishing. <https://doi.org/10.1016/B978-0-08-101029-7.00004-7>
- Ziolkowska, J. R. (2020). Biofuels technologies: An overview of feedstocks, processes, and technologies. *Biofuels for a more sustainable future*, 1-19. <https://doi.org/10.1016/B978-0-12-815581-3.00001-4>