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Biofuels for a Green Future: A Pathway to Environmental and Economic Sustainability

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ABSTRACT

Fossil fuels, no doubt have increased the prosperity and improved lifestyle Earth, but being the finite reserves of nature, they are costly and have also played a role in environmental pollution upsurge and health issues. Despite the increasing awareness of climate change, persistent elevated levels of greenhouse gases and other pollutants are observed. Environmental degradation outweighs the fossil fuels' derived energy. Fossil fuels contribute to global warming by the emission of CO₂, whereas biofuels offer carbon neutrality, reduced emission and biodegradability. Biofuels are environmentally friendly as they contain 10-45% oxygen content, and lower sulfur and nitrogen levels, which is unlikely with petroleum-based fuels. However, their sustainability can vary based on the feedstock choices, land-use practices and production methods. The objective of this review is to evaluate biofuel production levels and their potential as sustainable energy sources, with emphasis on their role in mitigating global warming. All four generations of biofuels have been discussed in this article with reference to their respective substrates, the techniques employed, and the final green energy products. The advantages and disadvantages of all four generations of biofuels have also been described. It can be concluded that due to being eco-friendly, biodegradable, cost-effective, and carbon-neutral, biofuels are promising alternate to conventional fossil fuels and can play an important role in the green economy.

1. INTRODUCTION

The energy emergency in Pakistan worsens annually because the nation produces electricity from imported fossil fuel (Agbulut and Saridemir, 2021; Kumar *et al.*, 2022). Pakistan faces intense economic and environmental challenges because of its heavy reliance on fossil fuel sources. For the past 30 years Pakistan conducted a steady transition of its economic base from farming to industrial development which led to greater fossil fuel consumption for manufacturing requirements. Fossil fuel reliance by Pakistan has produced

higher emissions of greenhouse gases and air contaminants especially within major urban zones. The large quantity of biomass waste produced by Pakistan's agricultural sector can serve as a primary material to create biofuels. Using Biofuels as an alternative energy would establish a green environment and boost Pakistan's economy while resolving its socioeconomic problems. Economic upsurge requires loads of fossil energy and power. In this text context, Pakistan has tremendously reliant on C-based fossils, for industrial production. *The Environmental Kuznet* curve describes that economic development is a key

factor in environmental degradation where there is a petite alertness for preserving the environment quality due to unattainability of modern technologies in the early economic development stages. As, during the initial period, developing countries have their focus on how they can boost their economy for the welfare of their population and thus disregard the quality of environment. Thereby, with economic upturn, not only the air pollution levels raise, but there is also seen the increasing consumption of carbon-based natural fossil fuel surpassing the manufacturing capability of industries and thus eventually leads to more GHGs (green-house gases) emission (Ali *et al.*, 2021). The tourism industry emits GHGs and is thus largely blamed for global warming (Banga *et al.*, 2022). Industrialization and fossil-fuel based automobiles have also played a role in the drastic GHG upswing where $1/5^{\text{th}}$ of CO_2 emission is because of transportation, while road transportation accounts for more than 70% in this matter (Jeswani *et al.*, 2020; Kumar *et al.*, 2022).

Most of the power producing stations use the limited means of fossil fuel like natural gas, diesel, and coal etc. (Karmaker *et al.*, 2020). Compared to other types, *coal* is the protuberant fossil fuel for the production of several harmful GHG and particulate matter because the power plants having low quality coal and employing older technologies, in turn escalate emission of CO_2 (Leonard *et al.*, 2020). *Natural gas*, another type of notable fossil fuel, is utilized in power generation, with two times less GHG emission as compared to coal-fired power plant. However, its resources worldwide are getting smaller due to usage in the cooking and transportation sector etc. Thus, a substitute of natural gas is imperious for power generation plants. *Petroleum* oil such as liquefied petroleum, heavy fuel oil, gasoline, and diesel based power generating plants are not only costly, but are also responsible for the

atmospheric emission of green-house gases (Karmaker *et al.*, 2020).

The six major cities of Pakistan were reported to have CO concentration ($\mu\text{g}/\text{m}^3$) during the daytime as: Quetta 8.1, Karachi 5.8, Rawalpindi 4.6, Lahore 4.6, Peshawar 3.5, and Islamabad 3.5. Another data analysis (2007–2010) represented high concentration of fine particulate matter (PM) in Lahore, Peshawar, Karachi, Islamabad, and Quetta as 143, 71, 88, 61, and 49 ($\mu\text{g}/\text{m}^3$) respectively. Lahore city was found to have daily and annual SO_2 concentration as 309 and 74 $\mu\text{g}/\text{m}^3$ respectively. Populous metropolitan cities like Quetta, Peshawar, and Karachi, were reported to have SO_2 concentrations as 54, 39, and 34 $\mu\text{g}/\text{m}^3$ respectively. During the same duration, Karachi, Lahore, Islamabad, and Peshawar were reported to have annual NO_2 concentrations of 46, 49, 49, and 52 $\mu\text{g}/\text{m}^3$ respectively, exceeding the safety borderline of 40 $\mu\text{g}/\text{m}^3$ by W.H.O. (air quality guidelines). In this mini review, biofuel generation has been compared and assessed for their challenges and opportunities.

2. FOSSIL FUELS- THREAT TO HUMAN HEALTH AND ENVIRONMENT

The long-term exposure to GHGs poses devastating impacts on humans as: 1) fatal lung diseases and pulmonary edema due to sulfur oxides and nitrogen oxides, 2) cardiovascular diseases, and 3) hyperventilation, asphyxia, and cellular anoxia (Hassan *et al.*, 2021). Burning of fossil fuels to meet the energy demands gravitate to release colossal amounts of GHGs like CO_2 , CO , SO_2 , NO_2 , and CH_4 , and impose egregious impacts on climate (Martins *et al.*, 2021; Kumar *et al.*, 2022). Nitrogen and sulphur oxides convert into respective acidic forms after dissolving in clouds and in turn cause acid rain and snow. According to the 2015 modeled data of ambient air pollution, loss of life expectancy (LLE)



strongly exceeds due to air pollution (Hassan *et al.*, 2021). Developed countries have their main focus on how to minimize the utilization of fossil fuels and lessen the carbon programs in the power sector, while in the developing countries, usage of fossil fuels is continuously increasing with no technologies to mitigate detrimental impacts. Thus, the rate of GHGs emission is more in those power sectors and ultimately cause damage to environmental sustainability (Karmaker *et al.*, 2020).

3. CLIMATE CHANGE AND GLOBAL WARMING

3.1 Climate

Earth climate covers the biosphere, the cryosphere (ice and snow), the ocean, the atmosphere, and the land. The *climate* is defined by characteristics, such as the amount of precipitation, the state of the snow and ice cover, air humidity, soil, temperature, and many other parameters.

3.2 Causes of Climate Change

Climate change is a menace for sustainable development and world economies. The Intergovernmental Panel on Climate Change (IPCC) argued that man-made or anthropogenic emissions of GHGs are significant and top contributors for the increase in average global temperature i.e. 1°C of global warming above the pre-industrial levels which are supposed to reach 1.5°C in 2030-2052. Change in global climate is at the helm for increasing the annual temperature of our planet in the 20th century (Mikhaylov *et al.*, 2020; Alola *et al.*, 2021; Gani, 2021; Welsby *et al.*, 2021). It is explained by 1) high levels of manufacturing and economic activity, and 2) alteration in the proportionality and concentrations of atmospheric GHGs i.e. carbon dioxide, methane, water vapors, perfluorocarbons, and ozone (Mikhaylov *et al.*, 2020; Abbasi *et al.*, 2022).

3.3 Effects of Climate Change

It results in decreasing agricultural production due to rise of temperature, seasonal fluctuations, and low rainfall. It also results in drought in many parts of the world where commercial farming can no longer be done. Water and soil degradation are likely to happen due to changes in precipitation and incessant temperature. It also aggravates desertification, ocean acidification, and changing weather conditions. However, increasing economic damage, food security, health problems, rising sea levels, severe storms affecting coastal areas, and migration are some immediate impacts of climate change.

4. CO₂ AND ENVIRONMENTAL DEGRADATION

Atmospheric emission of CO₂ is not directly involved in climate change, rather it first depletes the ozone layer, exposing the surface of Earth to UV radiation, ultimately leading to global warming which is then responsible for climate change i.e. an incessant shift in global/regional climatic patterns. Indiscriminate emission of CO₂ is accountable for environmental degradation in developing countries and is one of ten threats affecting the globe, as documented by the UN high-level panel on climate change, threats, and challenges. CO₂ emission is contributing to depletion of water, air, and soil like environmental resources, disruption of ecosystems, wildlife extinction, and an increased level of pollution.

The major types of environmental degradation include 1) Burning of Amazon (lungs of the Earth) which accounts of approximately 60% tropical forests; 2) Deforestation in which constant trees felling is reducing the supply of O₂, and limiting plant absorption of CO₂ which in turn will have detrimental effects on human health; 3) Excessive use of paper products coming from tree deforestation leads to the



production of vast amount of waste as these not usually recycled; 4) Soil degradation due to constant deforestation leaves the soil less nutritious and ultimately makes it difficult to cultivate again (Yoro and Daramola, 2020).

5. BIOFUELS AS THE RENEWABLE SOURCES OF ENERGY

5.1 Renewable Resources

By 2040, the global demand for energy is anticipated to rise by 28% approximately, compared to the contemporary levels (Osman *et al.*, 2021). Thus, there is utmost need to transit our energy dependence from carbon based fossil fuel to renewable sources, to reduce GHGs (human activities being among its primary drivers) which have drove the climate change, negatively impacting on a global scale (Kalair *et al.*, 2021; Liu *et al.*, 2021; Martins *et al.*, 2021; Plantinga and Scholtens, 2021). Conventional C-sources are being used for generating energy, but they are limited and proven harmful for the environment. Sustainable development programs focus on renewable energy sources (wind power, hydroelectric power, solar power, organic matter, etc.) which not only minimize global warming (thus mitigating climate change) but also reduce the wastes from the locality. There is a plenty of such renewable resources but their availability is dramatically dependent on the environmental situations and geographical positions and these are often overlooked for their potential adverse effects (Gibson *et al.*, 2017; Baidya and Nandi, 2020).

5.2 Concept of Green Energy and Biomass

5.2.1 Green Energy

The alternate/variant form of renewable energy, which is produced from biomass, solar, hydro, geo-thermal, or wind like ecofriendly resources, and has the ability to provide zero or nearly zero emissions of GHGs and air pollutants, and thus can diminish the greenhouse effect.

5.2.2 Green Power

Electricity generated from or supplied by readily renewable green sources (even more distributed than fossil/nuclear resources), which can help the developing country to boost their economy.

5.2.3 Sustainable system of energy

It involves the characters like continuity in energy development, energy flexibility, energy reliability, energy efficiency, cogeneration or CHP (combined heat and power), and environmental impacts. According to a report in 2005, the percentage consumption of these resources was seen as: 1% solar, 2% wind, 6% geo-thermal, 45% hydroelectric, and 46% biomass (Demirbas and Demirbas, 2010).

5.2.4 Biomass

It is a C-neutral fuel because it absorbs carbon from the atmosphere when it grows, which is then released into the environment when biomass is burnt. It has a short life span and the biofuels are derived from it through a variety of routes like biological, physical, chemical, and thermochemical (Chen *et al.*, 2019).

6. BIOFUELS

Fuels derived/produced from organic sources e.g. plants and their residual substances, agriculture crops, and by-products, that can alleviate the negative impacts of climate change, and slash the dependence on carbon based fuels and thus are regarded as a promising alternative (Jeswani *et al.*, 2020; Mahapatra *et al.*, 2021). It is expected that, by 2050, biomass is going to be the biggest sustainable energy source, as nearly 10-50% of the global demands will be fulfilled using it (Safari *et al.*, 2024). The classification system of biofuels alongside their biomass origins and uses is given in Figure 1 (Alam *et al.*, 2012; Sarwer *et al.*, 2022; Quevedo-Amador *et al.*, 2024).



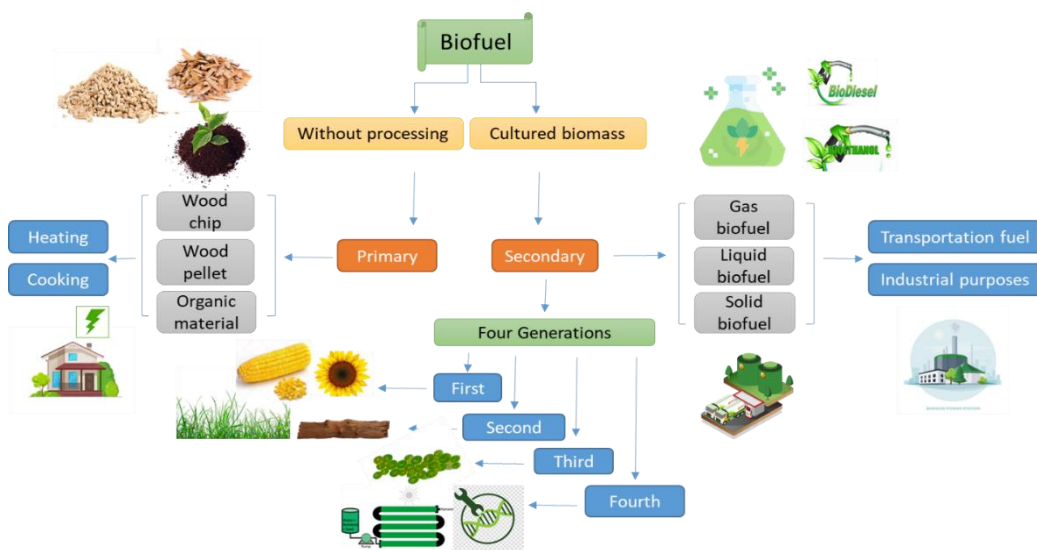


Figure 1. The classification system divides biofuels into four generations, starting from first generation of food crops (1G) through second generation of lignocellulosic biomass (2G) to third generation of algae (3G) and fourth generation of engineered biomass (4G). Their applications in transportation and power generation fields and additional sectors have also been given

6.1 Classification

Biofuels are classified into four generations, such as 1G/first, 2G/second, 3G/third and 4G/fourth generation (Lászlók *et al.*, 2020; Mat Aron *et al.*, 2020). The second and third generations are called as advanced/sustainable biofuels (Azad *et al.*, 2016). Sustainable Development Goals were formed by USA in September 2015, where several countries planned to incorporate approximately 20% biofuel in road transport (Mahapatra *et al.*, 2021). Sustainability is elucidated as addressing the needs of the contemporary generation without jeopardizing the future generation needs, ensuring the continuous fleshing of the economy, and preserving the needs of society and environment (Jeswani *et al.*, 2020; Lászlók *et al.*, 2020). Biofuels can either be used in their pure form or they can be used as additives; employed as a good alternative to conventional fuels; and can meet approximately 18% primary energy

consumption demands (Mahapatra *et al.*, 2021).

7. GENERATION OF BIOFUELS

7.1 First Generation Biofuels

The most common first-generation biofuels (bioethanol, biodiesel) are obtained from energy-containing molecules e.g. sugar, corn, sugarcane, soybean, palm oil, wastes, vegetable oil, animal fats, and others (Mohr and Raman, 2013; Khan *et al.*, 2021). Biodiesel and bioethanol are substitutes for diesel and gasoline respectively, where former is generated by the trans-esterification of oil obtained natural sources/leftover oils/fats while latter is produced through the sugar/starch fermentation. Approximately 80% liquid biofuel is generated from bioethanol while the rest is manufactured via biodiesel (Mahapatra *et al.*, 2021). Biofuel's evaluation criteria were based on two claims: 1) their explicit attempt to compete with crops and 2)



Table 1. Leftovers and the biomass's composition during biofuel production

Parameters	Crop type					
	Sugarcane Bagasse	Wheat & Wheat straw	Rice & Rice straw	Corn & Corn straw	Oat & Oat straw	Barley& Barley straw
Residual crop ratio	0.6%	1.3%	1.4%	1%	1.3%	1.2%
Carbohydrate	67%, 67.15%	35.85%, 54%	87.50%, 49%	73.70%, 58.29%	58.29%, 65.60%	67.10%, 70%
Lignin	14.5%	16%	7.13%	0.6%, 18.69%	4%, 13.75%	2.9, 9%

their economic, environmental, and energy balance will not be optimal as planned previously. These 1G biofuels have a severe footprint on food security and generate a limited amount of fuel (Mohr and Raman, 2013; Naqvi and Yan, 2015; Kumar *et al.*, 2019; Khan *et al.*, 2021). According to research, the creation of biofuels from agricultural waste as a raw material aids in reducing the severity of nutritional and environmental problems. The waste generated by various crops vary greatly and is given in Table 1 (Nisar *et al.*, 2024).

7.2 Second Generation Biofuels

To overcome the limitations of 1G biofuels, 2G biofuels were introduced where woody biomass and forest residues like non-edible feed stocks were used. Neither these compete with food crops nor require any specific land area or water supply for cultivation. Waste biomass (of short harvesting period) is directly used for biofuel generation, thus there is no requirement of feedstock cultivation, and they are consistently present for biofuel generation. Furthermore, they emit lower amounts of GHGs. But unlike the 1G biofuels, which can be used directly in bio-refinery processes, the 2G biofuels' biomass is required to undergo a series of pre-treatment in order to get the fermentable sugar. Thus, due to these limitations, a different source was looked for biofuel feedstock.

7.3 Third Generation Biofuels

The 3G biofuels are extracted using biomass obtained from microalgae which, compared to the plants, have a higher growth rate, and do not need an arable/big land area. Thus, there is no competition with agricultural crops, animal farms, and residential lands. Algae is reported to decrease the global atmospheric CO₂ level by 40%. It has attributes like carbon sink, thus various applications in the field of biotechnology are possible. Besides, microalgae are having the ability to produce a variety of biomolecules like carbohydrates, proteins, lipids, vitamins, and others. However, a large amount of nutrients and freshwater, for the cultivation of microalgae, elevates the overall cost. Use of wastewater as a source of food for microalgae can be an alternative option, as wastewater is nutrient rich and thus is regarded as the potential medium. However, as hazardous or unwanted chemicals are present in wastewater, there is a risk for microalgae contamination. These 3G biofuels are highly volatile, thus they are less stable compared to the 1G and 2G. Further, a high input of energy is needed for extracting the lipids and drying the biomass. Therefore, it led to exploration of the 4G biofuels.

7.4 Fourth Generation Biofuel

The 4G biofuels are obtained from the genetically modified microalgae which are



Table 2. Comparison of advantages and disadvantages of the various generations of biofuels

Biofuels	(1G) First-generation	(2G) Second-generation	(3G) Third generation	(4G) Fourth generation
Feedstock	Easily available crops, Edible	Non-food crops	Non-food crops	Non-food crops
Nutrients required	Fertilizers are required	Do not require fertilizer treatment	C and N sources are majorly required, nutrients can be reprocessed and solar energy can be also utilized.	Similar to 3G
Harvesting	Either by machine or by hand-picking	Similar to 1G	Harvesting of microalgae is financially expensive and complicated as well	Similar to 3G
Cost of manufacturing	Feasible economically	Less effective economically as conversion technology is bit complicated	Processes through which oils are extracted are expensive	Not only the initial investment but also the pilot setup is expensive
Use of pesticides/chemical fertilizers	Principally used	-	-	-
Water footprint	Portable water is required for biofuel generation	Similar to 1G	Waste, saline and/or non-portable water can be used for biofuel generation	Similar to 3G
Land footprint	Arable land	Arable land or forest	Non-arable land	Similar to 3G
Benefits	Easy conversion steps	It has less production costs and it does not affect the food chain	Food oil/ sea water/waste are among the cheap sources which can be used for obtaining raw materials	High energy, better growth rate, elevated lipid content, CO ₂ absorption



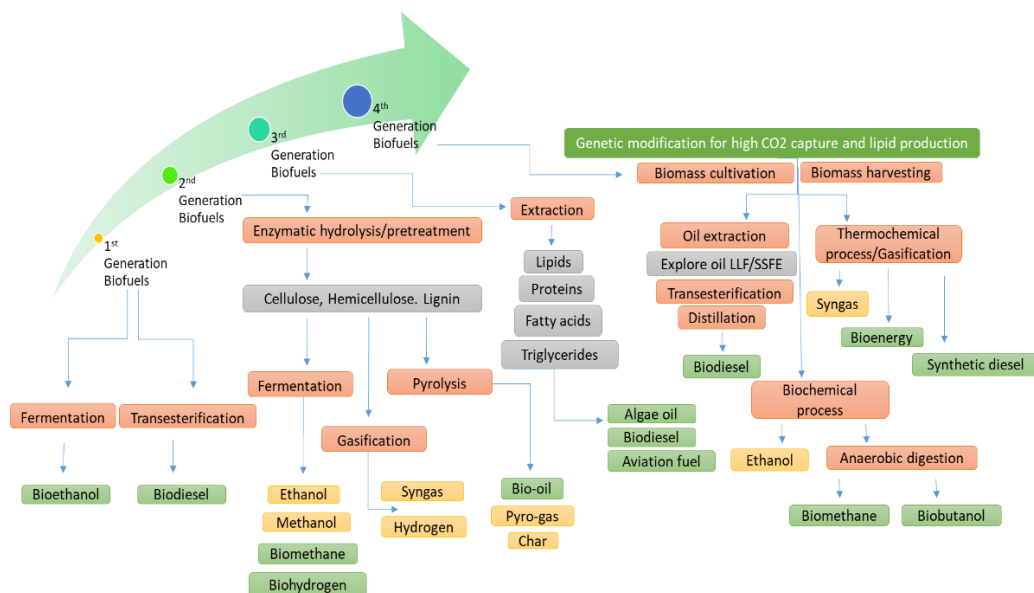


Figure 2. The schematic representation of the four generations of biofuels, highlighting the primary feedstocks, the key conversion processes and final green energy products obtained

carbon negative as these are having the ability to take up more CO₂, while the released amount is very less. This type of biofuel is aimed at 1) capturing large amounts of CO₂, 2) increasing the productivity of the biofuels, and 3) enhancing the microalgae adaptability in wastewater through advanced technologies, which have been expanded from RNA interference to metabolic, synthetic, systematic, and genetic engineering. However, due to the lack of gene/biological information, this technology does not apply to all microalgae species (Mat Aron *et al.*, 2020).

8. BIOFUEL PRODUCTION METHODOLOGIES

Biofuel manufacturing through various processes generates diverse environmental effects that incorporate land conversion impact and water usage together with greenhouse gas emission (Table 2) (Mat Aron *et al.*, 2020; Khan *et al.*, 2021; Mahapatra *et al.*, 2021; Shweta *et al.*, 2024). The categorization of

biofuels into different generations provides fundamental knowledge about their manufacturing approaches as well as their potential applications (Figure 2) (Nanda *et al.*, 2018; Malode *et al.*, 2022; Cavellius *et al.*, 2023; Shweta *et al.*, 2024).

8.1 Pyrolysis

The thermal breakdown of biomass that takes place in the absence of oxygen is known as pyrolysis. The word comes from the Greek words "pyro," which means fire, and "lysis," which means disintegration or breaking down into its component parts. Charcoal was produced in Southern Europe and the Middle East more than 5500 years ago using pyrolysis technology. Producing high-value bio-oil to rivals and eventually replacing non-renewable fossil fuels is the ultimate goal of this technology. As a result, in recent decades, pyrolysis has drawn increased attention as an effective technique for turning biomass into biofuel. In this process, the organic components in biomass undergo thermal



decomposition at 350 to 550 °C, in a non-reactive atmosphere i.e. in the absence of oxygen. Consequently, the long chains of carbon, hydrogen, and oxygen compounds in biomass disintegrate into smaller molecules that take the form of gases, condensable vapors (tars and oils), and solid charcoal. Each of these components decompose at a different rate and to a different extent depending on the reactor's configuration, feedstock, temperature, pressure, and other process variables. Process variables including temperature, catalyst, heating rate, etc. have a significant impact on both the yield and the quality of the pyrolysis products (Jahirul *et al.*, 2012; Pourkarimi *et al.*, 2019; Hoang *et al.*, 2021).

8.2 Hydrothermal Carbonization

Recent research has shown that the hydrothermal carbonization (HTC) method, also known as wet torrefaction, is the most desired option among available treatment options because it can process wet waste. With the HTC, the energy-intensive pre-drying procedure that is required for pyrolysis, dry torrefaction, and incineration, is eliminated. HTC operates in low temperature conditions (180–350 °C) and under autogenous pressure, which is the pressure produced during the carbonization process by the reactor. In HTC, biomass is immersed in a reactor containing the water to biomass ratio. The mixture is then heated to a subcritical temperature for a predetermined time (Lu *et al.*, 2012; Luz *et al.*, 2018).

HTC is an exothermic process that uses central reaction pathways like hydrolysis, dehydration, decarboxylation, polymerization, polycondensation, and aromatization to reduce the oxygen and hydrogen content of biomass. HTC biomass is a more environmentally friendly method of storing carbon because most of the carbon remains intact with the final product under acidic conditions and below 200 °C. The characteristics of solid fuel preparation for

handling, storage, and transportation can be greatly enhanced by HTC followed by densification or palletization. Because the HTC process requires less biomass preparation and treatment than other thermal treatment methods—primarily, pre-drying of wet waste is not required—it is a financially appealing choice. It has been shown that HTC can improve overall physicochemical properties and convert the entire range of biomass into the energy-dense solid fuel.

"Hydrochar" is the name given to the solid carbonaceous product produced by this process. Increased hydrophobicity and grindability of the solid formed during HTC suggest less issues with storage and transportation. Reaction time, temperature, pressure, and other process variables all affect how the final product is formed. Because hydro-char's chemical makeup and energy content are comparable to those of natural coal, it can be used as a solid fuel in traditional combustion processes. Hydrochar has various potential uses such as coal co-firing, pellets for power generation, volume reduction in waste treatment, and as a soil conditioner. It can also be used as carbon material for adsorption (Zhao *et al.*, 2014; Sharma *et al.*, 2020).

8.3 Anaerobic Digestion

An established technique, anaerobic digestion is currently in use for the conversion of primary and secondary sludge from wastewater treatment plants as well as the organic portion of municipal solid wastes. An elegant and cost-effective method which produces biogas / methane (Guiot and Frigon, 2012). However, more research is needed to maximize biogas production in a variety of scenarios. To ensure efficient and economical digestion, a number of factors have been taken into account when designing and operating digesters (Khelifi *et al.*, 2024). Anaerobic digestion (AD) breaks down waste materials into biomethane and two byproducts, digestate and effluent, which need



to be properly treated before being released into the environment. The slurry's high nitrogen content, pathogens, heavy metals, and indicator microbes limit its use on land. Nutrient-rich digestate/slurry in AD has higher concentrations of dissolved organic matter and inorganic nitrogen, such as ammonium, which leads to eutrophication. Notably, microalgal treatment of biogas slurry has been thoroughly studied. However, the method of cultivating microalgae in biogas slurry is also controversial because, following microalgal growth, the slurry has an unbalanced N/P ratio and a low C/N ratio, which negatively impacts algal growth. For this reason, effective slurry treatment techniques are being investigated; HTC is one such effective technique. HTC is an excellent technique for handling moist biogas slurry. HTC is a novel thermochemical process that uses subcritical water as a solvent and reactant at 180–350 °C and 2–5 MPa pressure to convert low-value wet biomass to hydrochar (Mathimani *et al.*, 2024).

8.4 Saccharification and Fermentation

Different techniques are employed to achieve fermentation and saccharification. These consist of simultaneous saccharification and fermentation (SSF) and separate hydrolysis and fermentation (SHF). Saccharification and fermentation are carried out in two steps in SHF, but they are combined into one step in SSF. The temperature in SSF is set by the microbe and usually does not go above 35°C, indicating that the enzymatic saccharification is not carried out under ideal circumstances. Nevertheless, even in the case of SHF, the reaction would still be impacted by end-product inhibition, a phenomenon in which the sugars produced by the hydrolysis of polysaccharides inhibit the cellulolytic enzymes. This inhibition occurs at the ideal temperature for enzymatic saccharification, which is normally 45°C–55°C. In SSF, end-product inhibition would not be an issue because the fermenting microorganism

consumes sugar (Tang *et al.*, 2024). Temperature, pH, enzyme loading, yeast strain and concentration, and solid content, are the primary variables influencing the SSF process. Due to the difference in ideal temperatures for enzymatic hydrolysis (45–50 °C) and fermentation (30–35 °C), temperature is a crucial component of SSF. The process conditions should be maintained within the pH range of 5.5–6.5 (Nisar *et al.*, 2024).

8.5 Transesterification

The most common method for producing biodiesel is trans-esterification, a direct process that requires the presence of the right catalyst and animal or vegetable oil. Trans-esterification was first used in 1846. Because of its ease of use and economic feasibility, trans-esterification is regarded as the most widely used technique and is superior to all others. Transesterification is the chemical reaction between alcohol and lipids that results in the production of fatty acid alkyl esters (FAAE) and glycerol. It requires supercritical conditions or catalysts to continue. Since the response is reversible, achieving 100% conversion is difficult. Trans-esterification has been pretreatment by esterification, which is done when utilizing feed stock of significantly lower quality. It is well known that ester formation is a uniformly catalyzed process that slows down when acids like HF, HCl, H₃PO₄, C₇H₈O₃S, and RSO₃H are present, which have the ability to ionize completely. The application of these homogeneous acids affects the corrosion of equipment. Many types of mixed catalysts, such as ZrO₂, TiO₂, SnO, sulfonic modified meso-structure silica, sulfonic ion exchange resin, and sulfonate carbon-based catalysts, have been used in esterification. To form esters with FFA (free fatty acids), a higher temperature (80–250 °C) is required (Govindhan *et al.*, 2024).

Temperature, time, the kind and concentration of the catalyst, the type of feedstock oil, and the



Table 3. Comparison of different catalytic methods for biodiesel production

	Advantages	Disadvantages
Homogeneous catalysts		
	Moderate operating conditions. Base catalysts have advantageous kinetics, producing a high yield quickly and with high activity. When compared to acid-catalyzed transesterification, base catalysts enable reactions 4000 times faster. Hydroxides are less efficient than basic methoxides. Esterification and transesterification can occur simultaneously using acid catalysts. Low grade oils are best suited for acid catalysts since they don't react with FFA or water.	Waste separation issue after reaction Formation of emulsions and saponification Reusing catalysts is not feasible restricted to reactors of the batch type. Basic catalysts react negatively to FFA and water. Elevated production costs in contrast to diverse types. Acid catalysts have a relatively low reaction rate and are corrosive. Higher methanol to oil molar ratios, higher temperatures, higher acid concentrations, and increased waste from the neutralization reaction are all necessary for acid catalysts.
Heterogenous catalysts		
	Sustainable, reusable, non-corrosive, and with less disposal issues Greater selectivity, easier product separation, and extended catalyst life Esterification and transesterification are catalysed simultaneously by heterogeneous acids that are insensitive to FFA and water. Comparatively inexpensive. In continuous fixed bed reactors, it is applicable.	Moderate conversion at the moment compared with highly active basic homogeneous. Limitation in mass transfer because to the three phases and the requirement for thorough mixing Pretreatments are necessary for high FFA feedstock, while basic catalysts necessitate low FFA and dehydrated conditions. High pressure, temperature, and alcohol to oil concentration are necessary. Acidic catalysts are more expensive than basic kinds due to their low acid source concentration and low microporosity.
Enzyme catalysts		
	Very particular. FFA is transformed into biodiesel. Low temperature of reaction and water insensitivity. Product separation ease greater yield compared to the basic catalysts. Able to be used as both heterogeneous and homogeneous catalysts	Expensive. Enzyme is impeded by methanol and may need to be diluted with additional supporting solvents.



alcohol-to-oil ratio are some of the variables that affect the yield of biodiesel during transesterification. In this process, alcohol with long chains, short chains, and cyclic chains are all utilized. However, methanol and ethanol are popular options because of their availability, polarity, superior reactivity, and low cost (Farouk *et al.*, 2024). The transesterification process yields a biodiesel component that is similar to that of traditional diesel and is widely used due to its advantages of mild reaction conditions and fewer by-products than during the preparation of biodiesel. The efficiency of the transesterification process is primarily determined by the type of reactions and the quality of the feedstock, with the performance of the catalyst being the key factor affecting the biodiesel yield. Three types of catalysts are used in the production of biodiesel: enzymatic, heterogeneous, and homogeneous catalysts. Homogeneous catalysts are the ones that are most often used to produce biodiesel. In general, adding a catalysis-based transesterification reaction boosts the rate of reaction and increases the product yield. There are several categories pertaining to the advancement of research into catalytic techniques that offer a simple, effective, and specialized pathway for the production of biodiesel (Wang *et al.*, 2023). To produce biodiesel from non-food, low-cost feedstocks, a significant amount of research effort has gone into refining the solid-acid catalyst (SAC) design. This is because SACs can perform triglyceride transesterification as well as esterification of FFAs without any of the disadvantages associated with using liquid acid catalysts, such as soap formation. Additionally, they enable continuous biodiesel production, which is a crucial step in the process intensification. Because these catalysts can be recovered and reused following esterification and transesterifications, they are appropriate for use in the commercial production of biodiesel. In order to simplify the generation of

SACs that have many desirable characteristics, new synthetic approaches are continuously being sought after. There are numerous solid acids given nowadays which are created to imitate liquid acid functions. On the other hand, solid acids are often more expensive, less stable, and less effective than their liquid counterparts (Guo *et al.*, 2023). Table 3 shows the advantages and disadvantages of different catalytic methods for biodiesel production (Ejikeme *et al.*, 2010; Atadashi *et al.*, 2013; Zhang *et al.*, 2016; Nasreen *et al.*, 2018; Tan *et al.*, 2019).

9. CONCLUSION

It is concluded that biofuels are more auspicious than fossil fuels. They can either be extracted from biomass or can be manufactured using organic materials e.g. plants/agricultural residues/other biological sources. They are biodegradable, thus have the ability to decompose instantly in the environment with the passage of time, and later are re-introduced in the environment without producing any contamination or persistent damage, thus rendering themselves as an ecologically sound alternate for traditional fossil fuels. They can be generated from renewable biological resources like plants and algae. If biomass conversion technologies are subjected to advancement, this will be a one of the potential avenues in enhancing the efficiency of biofuel production and profitability in industrial operations.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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