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Review Article: Biodiesel, In a Quest For Sustainable Renewable Energy: A Review on Its Potentials and Production Strategies

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ABSTRACT

The spike in the spontaneous discharge of greenhouse gas (GHG) emissions into the atmosphere and oil spills on land are placing the environment and natural systems under threat. These two contemporary challenges are heightened by the excessive exploitation of fossil fuels, coiled with rising energy demand pooled by population growth, and industrialization. Therefore, the quest for clean, low-cost, and sustainable energy is environmentally and economically driven. Energy from biomass especially biodiesel is poised to take a lead as an alternative to conventional diesel due to its renewability, non-toxicity, and less potent to GHG emissions. Hence, this paper put together the merits and demerits of the various renewable sources of energy, alongside the biodiesel production processes and output of some countries for the year 2020, which fell short of reporting. The first segment of this paper highlights the potential of biodiesel and its advantages over other renewable energies. The production output and various parametric effects were subsequently discussed for optimum biodiesel production. Then, the economic feasibilities and environmental benefits of biodiesel were emphasized among other attractive attributes of the fuel and enumerate gaps for future exploration.

List of content

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1. Introduction

The exhaustion of petroleum reserves and rising environmental emissions coupled with growing energy demand due to the population hike, constitute some of the global challenges today. The demand for fuel inevitably becomes larger soon considering the symmetrical increase in world population. Hence, finding alternative sources of fuel which are proficient to satisfy the growing energy demand remained a subject of interest among countries worldwide [1]. This is in a bid to reduce over-dependence on imported oil, diversify energy portfolios, derive to safeguard the environment by reducing carbon emissions footprint, and derive revenue influx from the biodiesel industry [2], though it is an undisputed fact that the exploitation and production of fossil fuels contributed immensely to the economic growth and drove the development of many countries. However, on the other hand, is considered as a curse especially now that the adverse effects of environmental emissions are resonating unpleasantly, leaving legacies such as flared gases, spills on land due to oil and gas exploration, and increasing heatwaves across the globe [3]. These GHG emissions are presently threatening the well-being of today and tomorrow's generations. Therefore, pollution abatement and mitigation of anthropogenic GHG emissions through green remediation technologies are vehemently needed to counter the effects of global warming and climate change. In this context, the current global thrive towards low carbon emission sources, signaled that the bulk of future energy must be derived from clean and renewable sources [4].

The uncertainty in prices of fossil-based fuels particularly crude oil in the international oil market, is another issue of steam concern among oil-producing countries, thereby making crude oil unstable and unpredictable [5]. Although the Organization of the Petroleum Exporting Countries (OPEC) influences the price of the commodity by regulating the production output and supply chain, this sometimes brought about a monopoly leading to rising economic and political conflicts among member countries [6]. Over-dependence on crude oil may be responsible for unrest among regions or member states, particularly among those ones relied heavily on it as a major revenue generator like Nigeria. This is because when the supply chain is broken, the market breadth is closed, and thus socio-economic welfare of the populace in the affected regions or countries is in jeopardy [7]. It is, therefore, obvious that the lack of sustainability of fossil fuels, paves the way for the need for renewables, as an alternative energy resource that is proficient to satisfy the ever-growing energy demand of today without compromising that of tomorrow. Thus, the paradigm shift from fossil fuel to renewables is a way to go (**Figure 1**), this would assist to limit the extreme weather and climate impacts posed by GHG emissions, while simultaneously ensuring clean and sustainable energy. In this context, biodiesel is considered a plausible and better candidate considering its renewability, sustainability, and low emission profile, which made it a cleaner-burning fuel with reduced emissions of CO_2 [8]. While other renewable energies such as solar, hydro, the wind are mainly utilized to power the electric grid, energy from biomass particularly biodiesel will in addition to provide electricity, will also support to quench the thirst for bulk liquid fuel demand by the transport sector, at the same time minimizing CO_2 emissions through photosynthetic process [9]. Therefore, this review put together the potentials and prospects of biodiesel compared to other renewables, discussed the types and suitable parameters for optimum biodiesel production, and underline the environmental benefit and economic feasibility of biodiesel, which was short felt of reporting in the literature of the best our knowledge.

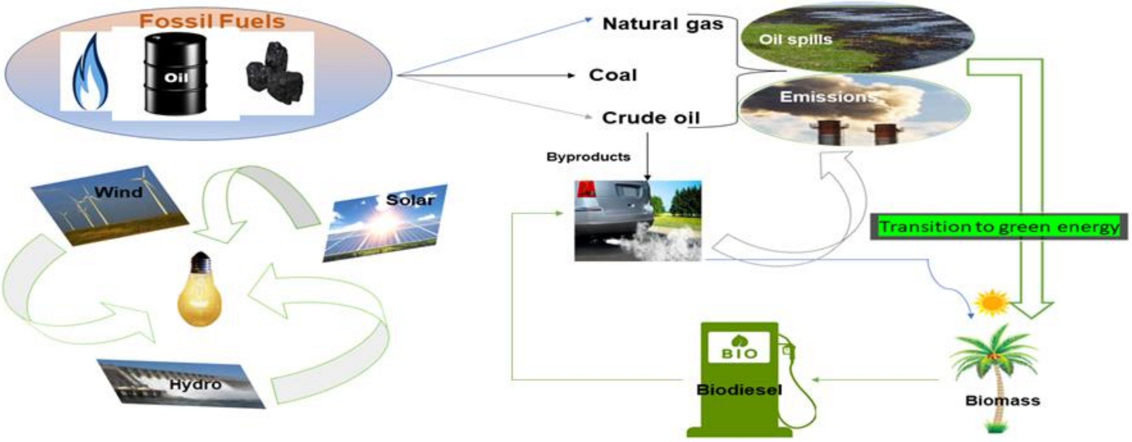

Figure 1. A scheme for paradigm shift from fossil fuel to renewable energy

1.1 Biodiesel in preference to other renewables energies

Energy derived from natural sources, that is non-depleting is simply called renewable energy. Looking at ASEAN countries, Malaysia is one of the countries that witnessed tremendous economic growth, and this worked out when the government initiate the utilization of renewable energy alongside fossil fuels in the country's energy mix since 1980, with the diversification policy came into play [10]. More recently in 2018, Malaysia passionately targeted a 20% infusion of renewable energy in its energy mix by 2025, the aim was to balance the utilization of other non-renewable energy resources, for the enhancement of energy security and stability. However, the use of hydropower is largely driven due to abundant water resources and represents the largest portion of renewable energy (86 %) in Malaysia's energy mix [4]. Interestingly, nature being a part of the environment becomes economically gainful by boosting the economy from hydropower plants via electricity generation to underpin industrial development, derive revenue, and provide employment opportunities. On the opposite side, hydroelectric dams are associated with several environmental issues, including water quality control and ecological problems.

Hydrogen fuel is also another potent source of energy, with about 74 % mass of the entire Universe. Unfortunately, its susceptible to liberate GHG emissions since hydrogen atoms are usually found in association with oxygen, carbon, and nitrogen and as a result, separating this bond requires a lot of energy [11]. Likewise, considering the proximity of Malaysia to the equator, abundant solar rays are present all year round and this proffers the utilization of solar energy for electricity generation in Malaysia [12]. Therefore, the derivation of renewable energy from solar is popular compared to the other renewables like hydro, wind, and wave energy for electricity generation. Although the cost of solar panels and other installation gadgets reduced significantly since 2010, which accounted for the economic expansion of the solar industry. Regrettably, despite the popular use of solar energy in urban areas, its implementation requires all-inclusive urban planning especially the synergy between solar energy and urban morphology [13]. Moreover, the hazardous substances accompanied by the production process and short life span of the solar modules are foreseen to foster serious environmental and economic consequences [14]. Consequently, these types of renewable energy (solar, hydro, and wind) have only made a tiny dent in the energy mix, as they are mainly used for electricity generation. Whereas the diversification target includes meeting the liquid fuel demand for industrial, commercial, and transport sectors. However, researchers are working further towards tapping energy from other renewables like nuclear waste and flying wind power to complement other renewables [15]. Thus, the need to explore other renewable energy options particularly energy from biomass.

Therefore, to achieve the ambitious goals of more than sixty countries binding to the Paris agreement of 2005, on the need to curtail the effects of climate change in a just and inclusive transition by bringing down carbon footprint to net-zero emissions by 2050, energy from biomass should be a critical player. This put to speed the production of biofuels and their blends such as bioethanol, biodiesel, and biogas, including bio alcohols like biopropanol, biobutanol, and biomethanol [16]. Bioenergy otherwise known as biofuel is a type of energy derived from organic materials (plants and animals). In other words, they are further produced from renewable sources through the process of biological carbon fixation. This form of energy is central to the pollution abatement of CO_2 emissions derived from fossil combustion through the process of photosynthesis [17]. Therefore, biofuels and other bioproducts would help to minimize the extreme of global warming. In 2020, the leading producing countries of biofuel were the USA, Brazil, and Indonesia, recording outputs as 1347, 884, and 283 petajoules, respectively. While Germany takes the lead in Europe with about 146 petajoules [18]. Generally, the growing demand for biofuels could be attributed to the compulsory use of this type of fuel and its blends in many countries. This is to reduce dependence on imported oil, support energy security mission, cut down GHG emissions, and drive towards the net-zero target, etc. In Malaysia, for instance, the government implemented many green energy policies to drive the local industry from 2001 to 2011, with energy from biomass particularly biodiesel being of keen interest, considering the abundance of palm oil as a major feedstock in the production of biodiesel [5]. Thereafter, Renewable Energy Act was gazetted in 2011 and has continuously been reviewed leading to the emergence of the National Biomass Strategy 2020 as the latest energy policy in Malaysia [4]. Thus, bioenergy is strategic in the context of the modern civilization and will continue to consolidate unabatedly toward meeting global energy stability.

Biogas is another type of renewable energy, but not green energy since is not close to carbon neutrality. It is produced by the degradation of microbial organic matter through an anaerobic process, a technique believed to be effective in converting biomass into energy for electricity, heating cooking, and transport fuel [19]. The technology for biogas production in most advanced countries like the USA and some European countries is taking to the next level. But on the contrary, in places like China and most Asian countries, the development of the biogas industry was barely close to none since the 1990s [20]. Nevertheless, there were some levels of improvements in biogas technology after years of research and experiments. This is augmented by the benefits of biogas in the areas of wastewater recycling, enhancing energy dependence, and the environmental conservation. While the high cost of producing biogas, biopropanol, and biobutanol affected their outspread. Moreover. Besides economic difficulty, other issues of concern are GHG emissions associated with biogas production from its composition [21]. Additionally, the need for professionals to handle and routinely maintain the biogas plant is crucial to its sustainability. Other problems include leakage from the reactor due to factors such as operational failure, shoddy piping, and excessive biogas strain which is attributed to the shutdown of biogas plants in many countries [20].

Bioethanol is likely another promising type of biofuel that has the potential to contribute to energy security. In 2020, about 142.9 billion liters of bioethanol were produced globally and were mostly consumed by the transport sector [22]. The USA and Brazil alone, produced about 84 % of the total production worldwide, followed by European countries representing 5 % of the total global output of 5443 million liters. Although, fuel ethanol is mainly produced from the fermentation of many feedstocks such as kernel, edible starchy crops, sugarcane, corn, barley, wheat, and lignocellulosic with many processes involved during production including fermentation, enzymatic hydrolysis, and gasification [23]. These are known as first-generation feedstock for bioethanol production and are widely embraced at an industrial scale. However, the USA and Brazil produces about 94% and 99% of the total bioethanol from corn and sugarcane, respectively in 2019. Additionally, similar edible feedstock types including wheat (18.7 %), maize (19.6 %), sugar beet (57.9 %), barley (1.9 %), and rye (1.9 %) were used in the production of bioethanol in European countries [24]. Consequently, the argument of food versus fuel competition for these feedstocks often declined the production rate of bioethanol [25]. Thus, the production of bioethanol shifted from biobased feedstocks to algal and industrial waste CO_2 often addressed as the third and the fourth-generation feed stocks, respectively [26]. Another issue of steam debate is that of neutrality of carbon emissions from bioethanol during production, in which a large quantity of CO_2 is liberated. Other problems associated with bioethanol include low energy content compared to gasoline, ease of moisture absorption leading to hydrolysis of bioethanol, high possibility of corroding metal engines, storage containers, difficulty to vaporize at low-temperature environment setting which often results in delaying engine starting, and susceptibility to enzymatic attack during fermentation [27]. Consequently, these are some of the factors which compromised the broader production of bioethanol and subsequently set the bar higher to produce biodiesel as the most preferred candidate.

Biodiesel is a renewable fuel which can be produced from oil crops, animal fats, or recycled oil through the transesterification process. This occurs when the oil or fats reacted with a solvent; (methanol, ethanol) in the presence of a catalyst; (acid, base, acid-base, or enzymes), to form fatty esters (biodiesel) and glycerol. One of the sole aims of the transesterification process is to lower the viscosity of the vegetable oil [28]. The produced fatty esters are considered environmentally friendly due to their low toxicity and are readily biodegradable. However, pyrolysis, micro-emulsification, blending with mineral diesel, esterification, and trans-esterification are the common methods of producing biodiesel but the latter seems to be the most frequently used method [29]. Several factors, such as catalysts type, reaction temperature, free fatty acid (FFA) contents, and alcohol to feedstock ratio have great influence in determining the success of the trans-esterification process [30]. Usually, a catalyst is used to improve the rate of the reaction and biodiesel, yield by shifting the equilibrium to the product side since the reaction is reversible [31]. Some of the benefits of biodiesel include a contribution to the growth of energy dependence, promoting resource conservation, protecting the environment, and creating job opportunities through improved social and economic prosperity which fosters the growth and development of rural economies [14].

2. Biodiesel production

The production and consumption of biodiesel have continued to grow exponentially with many countries developing interest as one of the leading alternative sources of energy. Reports by the World Bioenergy Association [32] revealed that in 2020, 144 billion liters of biofuels were generated worldwide, with biodiesel accounting for about 26 %, bioethanol contributing the lion’s share of 62 % while the remaining are from other sources. In 2020, the highest biodiesel production came from the USA, with a sum of 6.9 billion liters, followed by Brazil generating 6.3 billion liters and Argentina accounting for 1.6 billion liters. The statistics further show that Germany and France produced 2.49 and 2.09 billion liters, respectively. Furthermore, Indonesia take lead in Asia with 6.0 billion liters, while China and Malaysia, generated 1.5 and 1.2 billion liters, respectively with a linear projection that biodiesel production will increase significantly by 2030 [33].

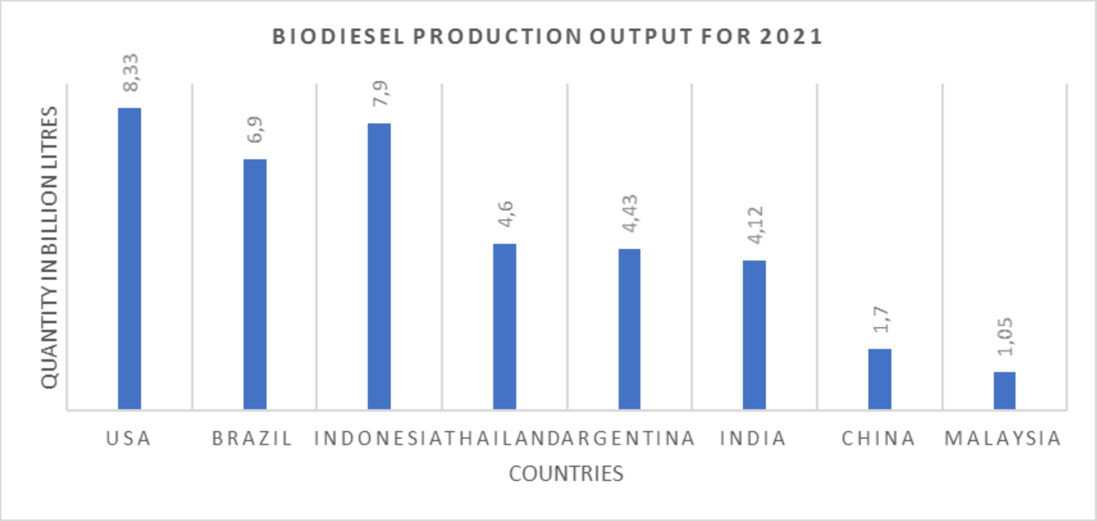

Figure 2. Biodiesel production output of some countries in 2021

Doubtless, **Figure 2** testifies that biodiesel is increasingly becoming a demanded commodity in the world today. However, ensuring sustainable biodiesel production and maintaining its longevity, remained a top priority. Because one major obstacle in the commercialization of biodiesel is the high cost of feedstock in many countries. In Europe, for instance, biodiesel is being sold at cheaper prices compared with petroleum diesel, due to the tax benefits given by the government to improve the potency of using biodiesel in various applications. Therefore, research-based, and profitable strategies for its production are consistently reviewed and upgraded to ensure sustainability. **Figure 3** shows a simple scheme for biodiesel production methods. These available processes for biodiesel production are blending the biodiesel with conventional diesel, esterification, transesterification, micro-emulsification, and pyrolysis [34].

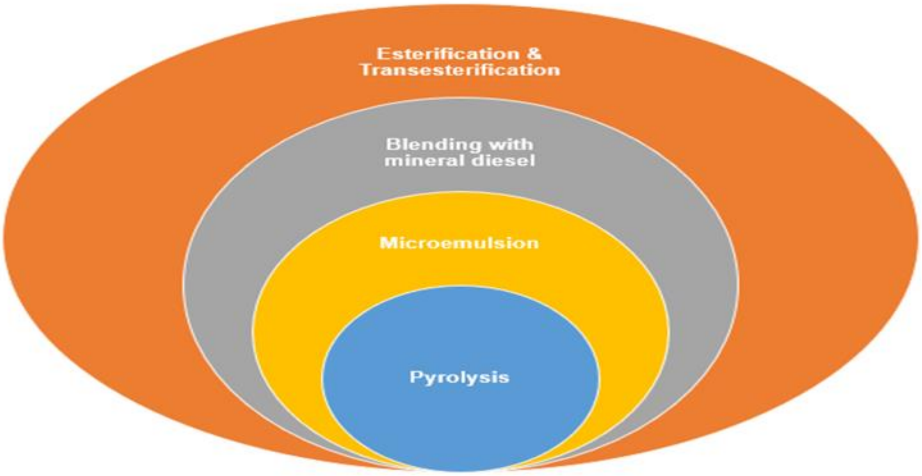

Figure 3. Methods for biodiesel production

2.1 Factors affecting biodiesel production

Biodiesel has received all-inclusive attention as a dependable substitute for conventional fuel in the past few years. This is evidenced by the growing biodiesel production in recent times, especially in the USA, Europe, and Asia. Although Covid-19 pandemic impacted the biofuels industry negatively, a total of 144 billion liters of biodiesel was produced globally in 2020, equivalent to 2480 thousand barrels per day (kb/d). The phenomenon represents about an 11.6 % decline from 2019 production output, and the first annual production cut recorded in the last two decades. Numerous works have been done to identify suitable parameters for optimum biodiesel production [35]. Yet, the choice of processing parameters and variables, particularly solvent, reaction temperature, and catalyst remained paramount. Several factors must be considered to attain an optimal production within the stipulated reaction time. Alcohol/oil ratios, temperature, catalyst nature, loading, stirring effects, and fatty acid composition of the oil are all the most influential parameters.

2.1.1 Types of catalysts

The choice of a suitable catalyst is considered as a key for the optimum trans-esterification process. Several works have been conducted using a homogeneous, heterogeneous, enzyme catalyst, ionic liquids, and carbon-based catalyst [36]. According to Chavan & Gaikwad [37], a base-catalyzed reaction tends to be faster than an acid-catalyzed homogenous reaction. This according to the authors, is due to their efficiency in facilitating reaction at low temperatures. Saluja et al., [38] reported that low cost, short reaction time, and ability to perform optimally at low temperature are some factors credited to the broader acceptability of base-catalyzed trans-esterification [39]. However, the wider acceptance of heterogeneous catalysts as the preferred option was attributed to their ability to work in both esterification and transesterification processes. Inevitably, the use of heterogeneous catalysts has its portion of weaknesses including high reaction temperature, pressure, catalyst concentration, and the possibility to corrode metal surfaces [40]. Alternatively, enzyme catalyst is currently trending in the research phase, with the possibility of taking over the chemical catalysts [41]. The use of enzymes catalyst for biodiesel production resolved the effect of longer reaction time during production, catalyst wastage, generation of side products, and vulnerability to high FFA [42]. Moreover, the use of ionic liquids (ILs) and non-catalyzed routes under supercritical conditions have currently been adapted and found to be successful on a laboratory scale by some researchers [43]. Nevertheless, high cost, non-product recovery, and low reusability were some of the identified operational problems as barriers to their large-scale industrial acceptance. **Table 1** reports the percentage yields, merit, and demerits of various types of catalysts. Therefore, transesterification using homogeneous catalysts remained the most favorable and applicable process for laboratory and industrial-scale biodiesel production.

Table 1. Classification of various types of catalyst

Type of catalyst	% Yield	Advantages	Limitations	Ref.
Homogenous acids e.g., HCl, H_2SO_4, HNO_3.	up to 99	- low cost - effective in producing, - high biodiesel yield, - insensitive to moisture, - no soap formation, - Suitable for transesterification and esterification reactions.	- poor refining ability, - and greater susceptibility to corrode pipelines, fuel tanks, and metal containers during storage, Slow reaction rate.	[44]
Homogenous bases e.g., NaOH, KOH	96-98	- low cost, - short reaction time, - perform optimally at low temperature,	- high possibility of soap formation in oils having FFA > 2.5 wt. %,	[39]

		- readily available.	- poor sensitivity to heat during transesterification, unresponsiveness to fatty acid	
Heterogenous acids e.g., ZrO2-Al2O3, WO3/ZrO3, SO4-2/TiO2-SiO2, etc.	<90	- improved ease of separation, - catalyst recovery after use, - relatively higher product yield, - insensitive to moisture and FFA content.	- requires high reaction temperature, pressure, and catalyst which leads to an increment in the overall production cost, - of product contamination due to leaching, - complex synthesis procedure leading to the high cost of the catalyst, - poor sensitivity to FFA, and the possibility to corrode metal surfaces, complicated and expensive.	[45]
Heterogenous bases e.g., ZnO, CuO.	<90	- fast reaction rate, - mild reaction condition, - easy product separation	- possibility of leaching catalyst, - prepared refined vegetable oil, non-recovery of glycerol.	[46]
Enzyme's catalyst	99	- resolved the effect of longer reaction time during production, - catalyst wastage, - minimize generation of side products and vulnerability to high FFA, - Insensitive to moisture, - Simple purification step.	- lack of product recover, - high cost, - non-recyclable, - slow reaction rate, low stability of most enzymes.	[47]
Ionic liquids (ILs) and non-catalyzed	-	- Serve as solvent and catalyst, - Easy product separation, - Act as amphoteric (behaving as acid and base catalyst).	high cost, - non-product recovery, - slow reaction rate, - low reusability	[43]
Carbon-based catalyst	<90	- high thermal stability, - reusability, - simple and chief synthesis.	- high alcohol to oil ratio, - high chances of forming leaching, - very slow rate. [48]	[48]

2.1.2 Types of feedstocks

The steam debate of food versus fuel competition for the edible crops as feedstock prompted the reviewed strategies towards using non-edible sources, micro-based algae, and waste from sludge, as feedstocks for biodiesel production. This is to cut down the cost of raw materials, accounting for the high cost of biodiesel and ensuring the sustainability of biodiesel production. However, the appropriateness of different feedstock types for effective biodiesel production is continuously been studied [49]. Although biodiesel can be prepared using either edible or non-edible oils, locally available and low-cost feedstocks are the two critical factors mostly considered when choosing a suitable feedstock for biodiesel production. Normally, the viability of non-edible oils as feedstock for biodiesel production is highly dependent on the number of fatty acids and free fatty acid (FFA) content present in the oils. The other interesting factors are the possibility of high oil yield from the feedstock, and the ability to withstand environmental influence after production [16]. The choice of feedstock for biodiesel synthesis is paramount and this is mainly hinged on the availability of the production site and cost. For instance, soybean oil is predominantly used in the USA, Argentina, and Brazil, while rapeseed oil is mainly utilized in Europe [33], palm oil and coconut oil in Southeast Asia mainly Malaysia and Indonesia [50], as presented in **Table 2**. However, with over 350 oil-bearing crops identified as potential feedstock sources for biodiesel production, the high cost of feedstock remained a major barrier to the broader utilization of biodiesel. This is due to the point that many countries resort to exploring their resources for use as feedstock for biodiesel production. **Table 3** presents a summary of the first, the second, the third, and the fourth-generation types of feedstocks with their merits and demerits. Therefore, researchers and biodiesel producers were energized owing to the availability of various feedstocks for producing biodiesel for compression ignition engine applications.

Table 2. Leading biodiesel producers, major used feed stocks, and price per litre in 2021

Rank	Region/countries	Predominant feedstock	The market price in USD/L	% Production share
1.	European Union	Rapeseed oil/waste oils	1.39	36
2.	USA	Soybean/other oils	B100, 1.4742	19
3.	Brazil	Soybean	B100, 0.59	12
4.	Indonesia	Palm oil	B20, 1.09	10
5.	Argentina	Soybean	-	7
6.	Thailand	Palm oil	B20, 0.84	4
7.	Malaysia	Palm oil	B10, 0.49	3.34
8.	China	Waste oil	-	3
9.	Columbia	Palm oil	-	1.5
10.	Canada	Waste oils	B100, 1.046	1.4

Table 3. Different types of feedstocks for biodiesel production

Type of feedstock	Advantages	Disadvantages	References
The first-generation (edible oils)	• Low cost, • Effective in production, • High biodiesel yield, • Readily available and affordable, • High oil content after extraction.	• Food versus fuel clash in the competition, • A decline in edible oil for consumption, • Excessive exploration leads to deforestation and destroying the ecosystem, • Only partly blended with conventional diesel.	[44]
The second generation (non-edible oils)	• Chiefly available, • High quality, less toxic, and better engine efficiency, • Zero cost, • Low sulphur and aromatic content, • Produced biodiesel meet ASTM requirements.	• High free fatty acid (FFA) content, thus greater possibility of soap formation, • Difficulty in collection, • High moisture content can cause hydrolysis of esters, • Intractable structure of the feedstock.	[25]
The third generation (micro-algae)	• High productivity per unit area and safer for storage, • Biodegradable and less toxic, • Have much greater oil production capacity than other oil crops, • Can grow in water ponds on non-arable land, saline water, and wastewater which are unsuitable for oil crops,	• Complex in harvesting and lipid extraction procedure, • microalgae as a feedstock for fuels is not economically viable, • Requires a high purity process, making it tedious, time-consuming, and cost, • High possibility of undergoing oxidative degradation due to predominant unsaturated fatty acids.	[51]

	• Reduce pollution by minimizing GHG emissions.		
The fourth generation (sludge waste)	• Zero cost, • Easy conversion rate, • Serve the dual purpose of converting waste into a value-added product, • Had a higher calorific value and neutral lipid.	• Easily undergoes microbial degradation, • High possibility of forming deposits during storage due to greater viscosity, • Have unpleasant smelt, presence of metal traces and toxic substances.	[48]

2.1.3 Reaction time, temperature, and type of solvent

Other process variables such as solvent type, temperature, reaction time, and alcohol to oil ratio are essential factors for the optimum biodiesel production. According to Srivastava et al. [34] for the stoichiometry of the reaction to shift to the product side, an alcohol to triglycerides molar ratio of 6:1 is primarily used in most trans-esterification processes. In such a process, the temperature is maintained at 60 ℃, and the reaction usually completes within one (1) hour. Similarly, research conducted by Refaat et al. [52] observed that 65 ℃, the reaction temperature is the optimum temperature for trans-esterification processes of many types of oils, with a reaction completion period of 30 min. Therefore, the conversion of oil to ester is mainly dependent on reaction time and temperature. Similarly, intense mixing is further another essential factor for a smooth trans-esterification process. According to the authors, effective stirring facilitates the dissolution of solute in the solvents, harmonizes the solution, and ultimately increases the reaction yield. Hence, 1000 rpm is the optimum stirring rate for both motionless and high-shear mixers. Moreover, solvent polarity plays a significant role in fast-tracking the rate of the trans-esterification process. Thanh et al. [53] reported that methanol is the most suitable solvent due to its greater polarity, easy recovery, and low cost. While Chai et al. [54] discovered that the use of tetrahydrofuran (THF) can speed up product separation after the trans-esterification reaction. Research carried out by Ho et al. [55] observed that polar solvents such as THF, DMF, ethanol, methanol, and water are suitable for improving the solubility, shortening the reaction time, and improving yield.

2.2 Economic feasibility and environmental benefits of biodiesel

As the demand and consumption of biodiesel are gradually increasing across the globe, producers of biodiesel are re-directing towards locally available, low-cost feedstock, and the cheap cost of production. This is to avail the affordability of the commodity at a lower rate compared with mineral diesel, for generous patronage. The broader acceptance of biodiesel at a commercial scale is hinged on its techno-economic feasibility, circumscribed by parameters such as the cost of raw materials particularly feedstock, production cost, and the market price of selling the produced biodiesel in comparison to mineral diesel, are key for the long-term viability of biodiesel production [56]. However, the effects of biodiesel on the global market prices are considered less significant due to the demand for the commodity. Therefore, factors considered for evaluating the viability of biodiesel production were operational costs comprising raw materials (feedstock price, chemicals, labor, and utilities), fixed charges (tax), and general costs such as insurance, transport, electricity, research, and development [57], all of which are binding to the profitability of biodiesel production which can be visible if the net present cost is lesser than the net present benefit. The cost of feedstock price is the key determinant factor for biodiesel cost, accounting for about 80% of the total production cost. However, the cost of catalysts and other chemicals has a negligible influence on the production cost. Because of this, the focus shifted from edible to non-edible, to erase the food versus fuel controversy and minimize cost. Likewise, the utilization of microalgae and sludge wastes, addressed as the third and the fourth-generation feed stocks respectively, were equally targeting cost reduction and conversion of the waste into value-added products in line with the circular economy. It is against this backdrop, that the Malaysian palm oil board (MPOB) established several methods to produce biodiesel from crude palm oil by-products [58], tailored toward reducing the cost of production, and minimizing the environmental problems associated with the generated wastes, in line with ensuring the sustainability and cost viability of biodiesel production.

Looking at the environment, utilizing biodiesel reduced hazardous emissions profile due to low carbon combustion. This supports GHG emission abatement strategies that heightened global warming and accelerate climate change [59]. The utilization of non-edible oils, microalgae, and waste from sludge help in remediating the environment. This is because the left-over accumulation of these wastes and their indiscriminate discharge in open spaces at some points liberates GHG such as CH_4 and N_2O that contaminate and often make the environment unattended, a common problem in both urban and rural areas. Therefore, biodiesel is considered as a promising type of fuel, because it is produced from various renewable sources which are less toxic, biodegradable, and environmentally benign. It is an oxygenated fuel with improved combustion efficiency, low carbon emission profile, and reduced risk of flammability. Furthermore, it is safer in terms of handling, storing, and transporting, due to higher flash points than mineral diesel. The absence of sulfur, and other aromatic compounds, coupled with low carbon content, minimizes CO emissions due to the low combustion profile [60].

3. Conclusion and future directions

The symmetrical growth in the world population day by day, coupled with increased emissions from fossil fuel combustion, ignited the quest for clean, affordable, and sustainable energy globally. As the population grows, more means of transportation become readily available, and this upends the growing demand for energy in the future. Thus, finding reliable, affordable, and sustainable clean energy would support quenching the energy thirst and remediating the confronting climate change induced by the influx of CO_2 and GHG emissions. Accordingly, the utilization of renewable energy resources particularly biodiesel, would contribute to the diversification policy for enhanced energy security, quench the thirst for the bulk liquid fuel demand, create a window for employment, and support revenue influx from biodiesel production. Therefore, besides the cost viability and availability of raw material, the other factors related to selectivity need to be considered to ensure biodiesel's high production yield and affordability. Concurrently, to replace mineral diesel with biodiesel substantially for usage in the transport and other sectors, the production of biodiesel needs to be expanded at the current rate. In conclusion, the following recommendations were made for future work towards improving the longevity and sustainability of biodiesel production.

- Despite the abundant waste especially from sludge and non-edible oils discarded at restaurants, researchers have not done enough towards exploring the potential of these types of feedstocks for biodiesel production. This will foster economic viability for low production costs, ensure sustainability, and promote bioremediation through waste recycling.
- In addition, little has been done on the utilization of fruit and vegetable wastes as bioethanol and bio-methanol in place of the conventional solvent for biodiesel synthesis. This will equally flow in line with the circular economy by converting waste to value-added products, while simultaneously fostering sustainability, waste recycling, and drastic reduction of production costs.
- Most naturally occurring feedstocks used in biodiesel synthesis, contained a certain quantity of natural antioxidants, which are considerably reduced or washed out during the oil refining process,

distillation, or purification. Thus, to address this issue, a new method called solvent-aided crystallization can be used to replace wet washing during purification. This is to preserve the natural antioxidants and eliminate the wastewater generation which needs further treatments afterward.

Other drawbacks to address include the issue of low energy content, poor oxidation stability, poor cold flow leading to filter blockage, poor ignition and volatility, incomplete combustion, and poor atomization, which ultimately compromise the engine compatibility, leading to increase maintenance cost and diminishing broader marketability of biodiesel.

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Authors' contributions

Dahiru A. Ajiya and Aisha A. Abdullahi midwifed the idea, Usman Bello, and Chinedu M. Agu performed most of the work by organizing and drafting the manuscript, Auwal A. Mahmoud, and Livingstone Udopia revised and carried out the proofreading, while Musa Muhammad and Nuruddeen M. Lawal prepared the tables including graphical illustrations. All authors went through and agreed to publish the manuscript.

Declaration of interests

The authors declare no competing interests.

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References

[1]. G. Ofosu-Peasah, E. Ofosu Antwi, W. Blyth, *Renew. Sustain. Energy Rev.*, **2021**, *148*, 111259. [Crossref], [Google Scholar], [Publisher]

[2]. U.K. Ibrahim, N. Kamarrudin, M.U.H. Suzihaque, S. Abd Hashib, *IOP Conf. Ser. Mater. Sci. Eng.*, **2017**, *206*, 012040. [Crossref], [Google Scholar], [Publisher]

[3]. U. Bello, L. Udofia, O.A. Ibitowa, A.M. Abdullahi, I. Sulaiman, K.M. Yahuza, *J. Geosci. Environ. Prot.*, **2021**, *09*, 151–167. [Crossref], [Google Scholar], [Publisher]

[4]. S.N.A. Latif, Chiong M.S., Rajoo S., Takada A., Chun Y.Y., Tahara K., Ikegami Y., *Energies*, **2021**, *14*, 1–26. [Crossref], [Google Scholar], [Publisher]

[5]. T.H. Oh, M. Hasanuzzaman, J. Selvaraj, S.C. Teo, S.C. Chua, *Renew. Sustain. Energy Rev*., **2018**, *81*, 3021–3031. [Crossref], [Google Scholar], [Publisher]

[6]. I.W. Ngarayana, J. Sutanto, K. Murakami, *IOP Conf. Ser. Earth Environ. Sci.*, **2021**, *753*, 012038. [Crossref], [Google Scholar], [Publisher]

[7]. N. Norouzi, *Adv. J. Chem. A. Theor. Eng. Appl. Chem.*, **2021**. *4*, 244–257. [Crossref], [Google Scholar], [Publisher]

[8]. S. Jain, M.P. Sharma, *Renew. Sustain. Energy Rev.*, **2010**, *14*, 667–678. [Crossref], [Google Scholar], [Publisher]

[9]. M. Sajjadnejad, S.M.S. Haghshenas, V. Tavakoli Targhi, H. Ghafarian Zahmatkesh, M. Naeimi, *Adv. J. Chem. A*, **2020**, *3*, 493–509. [Crossref], [Google Scholar], [Publisher]

[10]. S.E. Hosseini, M.A. Wahid, N. Aghili, *Renew. Sustain. Energy Rev.*, **2013**, *28*, 400–409. [Crossref], [Google Scholar], [Publisher]

[11]. IRENA, Hydrogen: a Renewable Energy Perspective, International Renewable Energy Agency, **2019**. [Google Scholar], [Publisher]

[12]. C.S. Good, G. Lobaccaro, S. Hårklau, *Energy Procedia*, **2014**, *58*, 166–171. [Crossref], [Google Scholar], [Publisher]

[13]. A. Giwa, A. Alabi, A. Yusuf, and T. Olukan, *Renew. Sustain. Energy Rev.*, **2017**, *69*,. 620–641.

[14]. [Crossref], [Google Scholar], [Publisher]
[15]. N. Gomesh, I. Daut, M. Irwanto, Y.M. Irwan, M. Fitra, *Energy Procedia*, **2013**, *36*, 303–312. [Crossref], [Google Scholar], [Publisher]
[16]. M.S. Hossain, M.I. Hossain, T. Jahangir, M. A. Hasan, *An Initiat. Int. Cent. Res. Resour. Dev.*, **2020**. [Crossref], [Google Scholar], [Publisher]
[17]. A. Demirbas, *Energy Convers. Manag.*, **2008**, *49*, 2106–2116. [Crossref], [Google Scholar], [Publisher]
[18]. J. Barber, P.D. Tran, *J. R. Soc. Interface*, **2013**, *10*, 20120984. [Crossref], [Google Scholar], [Publisher]
[19]. Statista, "Biodiesel Magazine of United State." **2020**. [Publisher]
[20]. B. Molinuevo-Salces, A. Mahdy, M. Ballesteros, C. González-Fernández, *Renew. Energy*, **2016**, *96*, 1103–1110, [Crossref], [Google Scholar], [Publisher]
[21]. I.S. Chang, J. Zhao, X. Yin, J. Wu, Z. Jia, L. Wang, *Renew. Sustain. Energy Rev.*, **2011**, *15*, 1442–1453. [Crossref], [Google Scholar], [Publisher]
[22]. T. Seljak, K. Pavalec, M. Buffi, A. Valera-Medina, T. Katrasnik, D. Chiaramonti, *J. Eng. Gas Turbines Power*, **2019**, *141*, 1–9. [Crossref], [Google Scholar], [Publisher]
[23]. A. Duque, C. Álvarez, P. Doménech, P. Manzanares, A.D. Moreno, *Processes*, **2021**, *9*, 1–30, [Crossref], [Google Scholar], [Publisher]
[24]. C. Piccolo, F. Bezzo, *Biomass Bioenerg.*, **2009**, *33*, 478–491. [Crossref], [Google Scholar], [Publisher]
[25]. N. Kumar, Varun, S.R. Chauhan, *Int. J. Ambient Energy*, **2016**, *37*, 121–135. [Crossref], [Google Scholar], [Publisher]
[26]. M. Munir, M. Ahmad, M. Saeed, A. Waseem, A.S. Nizami, S.Sultana, M. Zafar, M. Rehan, G.R. Srinivasan, A.M. Ali, M.I. Ali, *Renew. Sustain. Energy Rev.*, **2021**, *138*, 110–115. [Crossref], [Google Scholar], [Publisher]
[27]. L. Gouveia, A.C. Oliveira, *J. Ind. Microbiol. Biotechnol.*, **2009**, *36*, 269–274. [Crossref], [Google Scholar], [Publisher]
[28]. Z. Yaakob, B.N. Narayanan, S. Padikkaparambil, S. Unni K., M. Akbar P., *Renew. Sustain. Energy Rev.*, **2014**, *35*, 136–153. [Crossref], [Google Scholar], [Publisher]
[29]. S.S. Prasad, A. Singh, *SN Appl. Sci.*, **2020**, *2*, 1–9. [Crossref], [Google Scholar], [Publisher]
[30]. K.A. Zahan, M. Kano, *Energies*, **2018**, *11*, 1–25. [Crossref], [Google Scholar], [Publisher]
[31]. U. Bello, G.A Shallangwa, S.O. Idris, M. Musa, A.A. Aisha, *Bayero J. Appl. Sci.*, **2018**, *11*, 136–141. [Crossref], [Google Scholar], [Publisher]
[32]. S.S. Pantoja, L.R.V. Da Conceição, C.E.F. Da Costa, J.R. Zamian, G.N. Da Rocha Filho, *Energy Convers. Manag.*, **2013**, *74*, 293–298. [Crossref], [Google Scholar], [Publisher]
[33]. W. B. Association, "Global Bioenergy Statistics," World Bioenergy, **2020**, 1–64. [Publisher]
[34]. A. Galadima, O. Muraza, *J. Clean. Prod.*, **2020**, *263*, 121–135. [Crossref], [Google Scholar], [Publisher]
[35]. N. Srivastava, M. Srivastava, V.K. Gupta, A. Manikanta, K. Mishra, S. Singh, S. Singh, P.W. Ramteke, P.K. Mishra, *3 Biotech*, **2018**, *8*, 1–11. [Crossref], [Google Scholar], [Publisher]
[36]. N. Yusuf, S.K. Kamarudin, Z. Yaakub, *Energy Convers. Manag.*, **2011**, *52*, 2741–2751. [Crossref], [Google Scholar], [Publisher]
[37]. M. Hamza, M. Ayoub, R.B. Shamsuddin, A. Mukhtar, S. Saqib, I. Zahid, M. Ameen, S. Ullah, A.G. Al-Sehemi, M. Ibrahim, *Environ. Technol. Innov.*, **2021**, *21*, 101–120. [Crossref], [Google Scholar], [Publisher]
[38]. S. Chavan and A. Gaikwad, *Biomass Bioenerg.*, **2021**, *144*, 105897. [Crossref], [Google Scholar], [Publisher]
[39]. R.K. Saluja, V. Kumar, R. Sham, *Renew. Sustain. Energy Rev.*, **2016**, *62*, 866–881. [Crossref], [Google Scholar], [Publisher]
[40]. H. Wang, Y. Pu, A. Ragauskas, B. Yang, *Bioresour. Technol.*, **2019**, *271*, 449–461. [Crossref], [Google Scholar], [Publisher]
[41]. I. del Campo, I. Alegría, M. Zazpe, M. Echeverría, I. Echeverría, *Ind. Crops Prod.*, **2006**, *24*, 214–221. [Crossref], [Google Scholar], [Publisher]
[42]. J.S. Sidhu, T.A. Zafar, *Food Qual. Saf.*, **2018**, *2*, 183–188. [Crossref], [Google Scholar], [Publisher]
[43]. S. Liu, Z. Wang, S. Yu, and C. Xie, *Bull. Chem. Soc. Ethiop.*, **2013**, *27*, 289–294. [Crossref], [Google Scholar], [Publisher]
[44]. B.Y. Han, T. Li, R.Q. Deng, X.F. Xiong, C.Y. Chen, *Appl. Mech. Mater.*, **2013**, *389*, 46–52. [Crossref], [Google Scholar], [Publisher]
[45]. M.D. Putra, I.F. Nata, C. Irawan, *Data Br.*, **2020**, *28*, 104879. [Crossref], [Google Scholar],

[Publisher]
[46]. F. Aladedunye, R. Przybylski, B. Matthaus, *Crit. Rev. Food Sci. Nutr.*, **2017**, *57*, 1539–1561. [Crossref], [Google Scholar], [Publisher]
[47]. I.M. Atadashi, M.K. Aroua, A.R. Abdul Aziz, N.M.N. Sulaiman, *Renew. Sustain. Energy Rev.*, **2012**, *16*, 3456–3470. [Crossref], [Google Scholar], [Publisher]
[48]. L.C. Meher, M.G. Kulkarni, A.K. Dalai, S.N. Naik, *Eur. J. Lipid Sci. Technol.*, **2006**, *108*, 389–397. [Crossref], [Google Scholar], [Publisher]
[49]. J.M. Marchetti, V.U. Miguel, A.F. Errazu, *Renew. Sustain. Energy Rev.*, **2007**, *11*, 1300–1311. [Crossref], [Google Scholar], [Publisher]
[50]. M. Takase, W. Feng, W. Wang, X. Gu, Y. Zhu, T. Li, L. Yang, X. Wu, *Fuel Process. Technol.*, **2014**, *123*, 19–26. [Crossref], [Google Scholar], [Publisher]
[51]. R. Nelofer, R.N. Ramanan, R.N.Z.R. Abd Rahman, M. Basri, A.B. Ariff, *Ann. Microbiol.*, **2011**, *61*, 535–544. [Crossref], [Google Scholar], [Publisher]
[52]. Y. Nan, J. Liu, R. Lin, L.L. Tavlarides, *J. Supercrit. Fluids*, **2015**, *97*, 174–182. [Crossref], [Google Scholar], [Publisher]
[53]. A.A. Refaat, N.K. Attia, H.A. Sibak, S.T. El Sheltawy, G.I. ElDiwani, *Int. J. Environ. Sci. Technol.*, **2008**, *5*, 75–82. [Crossref], [Google Scholar], [Publisher]
[54]. L.T. Thanh, K. Okitsu, L. Van Boi, Y. Maeda, *Catalysts*, **2012**, *2*, 191–222. [Crossref], [Google Scholar], [Publisher]
[55]. F. Chai, F. Cao, F. Zhai, Y. Chen, X. Wang, Z. Su, *Adv. Synth. Catal.*, **2007**, *349*, 1057–1065. [Crossref], [Google Scholar], [Publisher]
[56]. L.H. Ho, N.F. Ramli, T.C. Tan, N. Muhamad, M.N. Haron, *Sains Malaysiana*, **2018**, *47*, 99–107. [Crossref], [Google Scholar], [Publisher]
[57]. A.T. Brimmo, A. Sodiq, S. Sofela, I. Kolo, *Renew. Sustain. Energy Rev.*, **2017**, *74*, 474–490. [Crossref], [Google Scholar], [Publisher]
[58]. M.A.H. Shaah, M.S. Hossain, F.A.S. Allafi, A. Alsaedi, N. Ismail, M.O. Ab Kadir, M.I. Ahmad, *RSC Adv.*, **2021**, *11*, 25018–25037. [Crossref], [Google Scholar], [Publisher]
[59]. S. Sumathi, S.P. Chai, A.R. Mohamed, *Renew. Sustain. Energy Rev.*, **2008**, *12*, 2404–2421. [Crossref], [Google Scholar], [Publisher]
[60]. A.W. Nursulihatimarsyila, K.Y. Cheah, T.G. Chuah, W.L. Siew, T.S.Y. Choong, *Am. J. Appl. Sci.*, **2010**, *7*, 434–437. [Crossref], [Google Scholar], [Publisher]
[61]. S. Kalligeros, F. Zannikos, S. Stournas, E. Lois, G. Anastopoulos, C. Teas, F. Sakellaropoulos, *Biomass Bioenerg.*, **2003**, *24*, 141–149. [Crossref], [Google Scholar], [Publisher]

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