Biofuels for Internal Combustion Engine

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Biofuel, a cost-effective, safe, and environmentally benign fuel produced from renewable sources, has been accepted as a sustainable replacement and a panacea for the damaging effects of the exploration for and consumption of fossil-based fuels.

Keywords: biofuel ; biodiesel ; emission ; feedstock ; utilization ; transesterification ; transportation

1. Biofuel as a Renewable Fuel

Since the early 1970s, when the word “biofuel” was first used, authors have defined the term as: (a) a fuel manufactured either from or by fresh, living micro- or macro-organisms [1]; (b) a fuel made directly or indirectly from biomass [2]; (c) a liquid fuel obtained from biomass, e.g., biodiesel produced from fats and oils, biogas generated from animal waste, etc. [3]; (d) a bio-based fuel naturally obtained from wood and wood chips or agricultural residues or chemically converted from biomass to charcoal, biodiesel, bioethanol, and biomethane [4]. Using these definitions, we can summarize that biofuel is generated from plants, animal waste, manure, sludge, etc., in either a solid, liquid, or gaseous form, and is capable of being converted to another variety of biofuel [5]. Major benefits and paybacks derivable from the deployment of biofuels as a form of renewable fuel include:

- Biofuels are renewable and are carbon- and CO2/GHG-neutral during the progression of the life cycle [6].
- Less GHG emissions are generated from the utilization of biofuels compared to FB fuels [7][8].
- Biofuels are biodegradable, sustainable, and environmentally benign [9][10].
- Biofuels are largely produced from locally available and accessible resources, applying safe production methods [11][12].
- Production and utilization of biofuels enhance home-grown agricultural development and investment [13][14].
- Biofuels provide improvements in the health and living conditions of people [13][14].
- Biofuels create jobs and improvements in local livelihoods and reduce energy importations [15][16].
- Economically, biofuel helps to stabilize energy prices, conserve foreign exchange, and generate employment at the macroeconomic level [17][18].
- Household usage of biofuel does not trigger life-threatening health conditions, as opposed to FB fuels [19][20].

Notwithstanding these advantages, the high initial cost of production and storage of biofuels can be a deterrent for potential producers and users. There are justifiable concerns that the increased demand for biofuel will increase the cost of the relevant agricultural and woody raw materials, as well as other feedstocks [21][22]. Also, continuous demand for wood can lead to rapid deforestation, while huge parcels of land are required to cultivate special trees and other inedible oils for biofuel production. In specific terms, methane, a major component of biogas, is a major contributor to global climate change and continuous usage of biogas can exacerbate ozone layer depletion [23], while biodiesel, a form of biofuel, generates high NOx emission and contributes to higher engine wear compared to FB fuel [24]. Despite the obstacles, biofuel is a clean, sustainable, and affordable energy resource choice that can replace FB fuels and rescue humankind from the looming environmental disaster. The adaptation of biofuels as sustainable fuels in various sectors of the economy is one of the strategies for CO2 reduction and carbon mitigation [25][26].

2.1. Classification of Biofuels

2.1.1. Classification Based on the Physical State

Solid Biofuels

Generally, any solid biomass material can be described as solid biofuel. Solid biomass is principally any solid feedstock that can be converted into biofuel [27]. Examples of such solid biomass include lignocellulosic biomass and various types of solid waste [28]. **Table 1** shows various categories of solid biofuel and their examples. Ideally, each of these raw solid biomasses can be used directly as solid biofuels or as feedstock for other forms of biofuel production.

Table 1. Categories and examples of solid biofuel [29][30][31][32][33].

Lignocellulosic Biomass			Solid Waste
Agricultural Residues	**Forest Residues**	**Energy Crops**	
Rice straw Rice husk Wheat straw Sorghum straw Corn stover Sugarcane bagasse Sugarcane peel Barley straw Olive pulp Grapeseed	Firewoods Wood chips Wood branches Sawdust Fruit bunch Willow chips Black locust Pine Spruce Eucalyptus Softwood Hardwood Hybrid poplar	Switchgrass Miscanthus Energy cane grass Hybrid Pennisetum Triarrhena lutarioriparia Energy cane leaf Energy cane stem Grass leaf Grass stem	Municipal solid waste Processed paper Plastics Wastewater sludge Food waste Dried animal manure Poultry waste

Compiled by the authors.

Liquid Biofuels

Liquid biofuels refer to any renewable fuel in liquid form. They are mainly used as transport fuels. Notable examples of liquid biofuels are biodiesel, biomethanol, bioethanol, biobutanol, biopropanol, bio-oil, jet fuel, etc. [34][35][36].

Gaseous Biofuels

Biogas/biomethane, biohydrogen, and biosyngas are the commonest examples of gaseous biofuels. They have a wide variety of applications, including for thermal, transport, and heat uses and electricity/power generation.

2.1.2. Classification Based on Technology Maturity

According to the degree of technology maturity or status of the commercialization technologies, biofuels are often categorized as conventional biofuels and advanced biofuels, as shown in **Figure 1**.

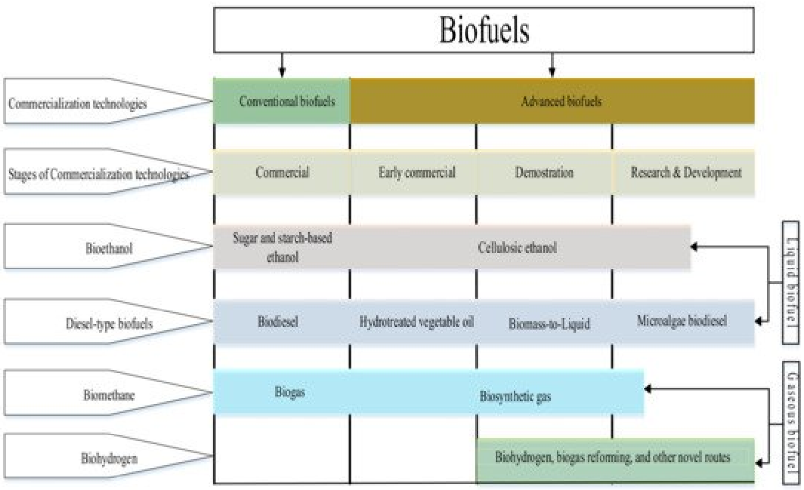

Figure 1. Classification of biofuels based on technology maturity. Adapted from [37]. Developed by the authors.

2.1.3. Classification Based on the Generation of Feedstock

Feedstocks for biofuel production are divided into three categories in terms of their generation: first-generation feedstock, second-generation feedstock, and third-generation feedstock. The choice of feedstock has a huge influence on the development and utilization of biofuel as a substitute for FB fuels. Feedstocks are chosen based on price, hydrocarbon content, and biodegradability. For example, edible feedstocks and those containing pure sugars are relatively expensive. Simple sugars are preferred as feedstocks because they are easy to decompose with microbes while lignocellulosic biomasses are selected based on their relative affordability.

2.1.4. Classification Based on the Generation of Products

Primary Biofuels

The main feature of primary biofuels, also known as natural biofuel [38] or zero-generation biofuel, is that they are used the way they occur without any modifications, alterations, processing, or pre-treatment. Examples of primary biofuels include firewood, wood chips, pellets, animal waste, forest and crop residues, and landfill gas. Notable areas of application of primary biofuels include cooking, household heating, brick kilns, drying, roasting, and electricity generation. This type of biofuel is readily available and its utilization does not require any special skill or infrastructure. However, their utilization is crude, compromises air quality, and may negatively impact the health of the user [39][40].

First-Generation Biofuels

The need to get a sustainable and viable alternative to finite energy sources gave rise to the development of First Generation Biofuels (1GB). Major examples include biodiesel, biogas, bioalcohols, biosyngas, biomethanol, and bioethanol. Major feedstocks for the production of 1GB include edible (food) crops like corn, wheat, palm oil, soybeans, edible vegetable oil [41], rapeseed, Karanja, Moringa oleifeara, Jatropha curcas [42], corn, cereals, sugar cane, wood, grains, straw, charcoal, household waste, and dried manure [43]. Though 1GB is biodegradable and offers great environmental and social benefits, the food vs. fuel trade-off and extensive area and time required to grow the inedible feedstock are some of its drawbacks [44]. Also, the high cost of feedstock, which was found to consume over 70% of the generation cost, is discouraging [45][46][47].

Second-Generation Biofuels

Second-Generation Biofuels (2GB), which were developed as a solution to some of the drawbacks associated with 1GB, can be produced from inedible feedstocks like waste cooking oil [48], waste animal fats [49], recovered oil [50], and lignocellulosic biomass, like grass, wood, sugarcane bagasse, agricultural residues, forest residues, and municipal solid waste [51][52], as well as from bioethanol, biodiesel, biosyngass, biomass to liquid biodiesel conversion, bio-oil, biohydrogen, bioalcohols, biodimethylfuran, and bio-Fischer–Tropsch [53][54]. The generation of 2GB does not affect the food chain and the cost of feedstocks is relatively low, but the production technologies are still complex and have not been commercialized yet [55][56].

Third-Generation Biofuels

The challenges associated with 1GB and the 2GB gave rise to the development of the Third Generation Biofuels (3GB), particularly with regard to feedstock selection. Algae, which is the major feedstock for 3GB, does not interfere with the food chain and requires no land or freshwater for cultivation, either naturally or artificially [57]. Other feedstocks for 3GB include yeast, fungi, and cyanobacteria, while examples of 3GB include bioethanol, vegetable oil, biodiesel, biomethanol, and jet fuels. In recent years, 3GB has attracted more investment, particularly in algae cultivation and conversion technologies [58].

Fourth-Generation Biofuels

Fourth Generation Biofuels (4GB) are produced from genetically or metabolically engineered feedstock from algae. Unlike 2GB and 3GB, the production of this generation of biofuels ensures sustainable production and catches CO2 emissions from oxygenated fuel combustion throughout the entire production progression [59]. The application of production technologies has drastically reduced the cost of production, making it economically competitive. Major examples of 4GB include hydrogenated renewable diesel, bio-gasoline, green aviation fuel, vegetable oil, and biodiesel.

2. Biofuel as Internal Combustion Engine Fuels

Transportation is one of the necessities of life and a major contributor to the socio-economic growth of countries. The ease of the movement of goods and services is one of the measures of the quality of life of individuals. Governments across jurisdictions devote significant efforts and resources to ensure affordable and safe transportation services. The transportation sector consumes over 90% of the total FB fuel products and over 25% of global energy [60][61]. The proportion of the total energy used for on-road transport is projected to increase from the present 28% to 50% by 2030 and further to 80% by 2050 [62]. The total energy consumption in the transport sector was 110 million TJ in 2015 including passenger vehicles (cars and bikes), buses, air, passenger rail, and air freight. Heavy trucks, light trucks, and marine transport jointly consume 35% of the transportation sector energy, as shown in **Figure 2** [63][64]. The 129 billion liters of liquid biofuel used in 2016 is projected to rise to 652 billion liters by 2050, while about 180 billion liters of biodiesel will be needed in the transport sector in 2050, as shown in **Figure 3** [65].

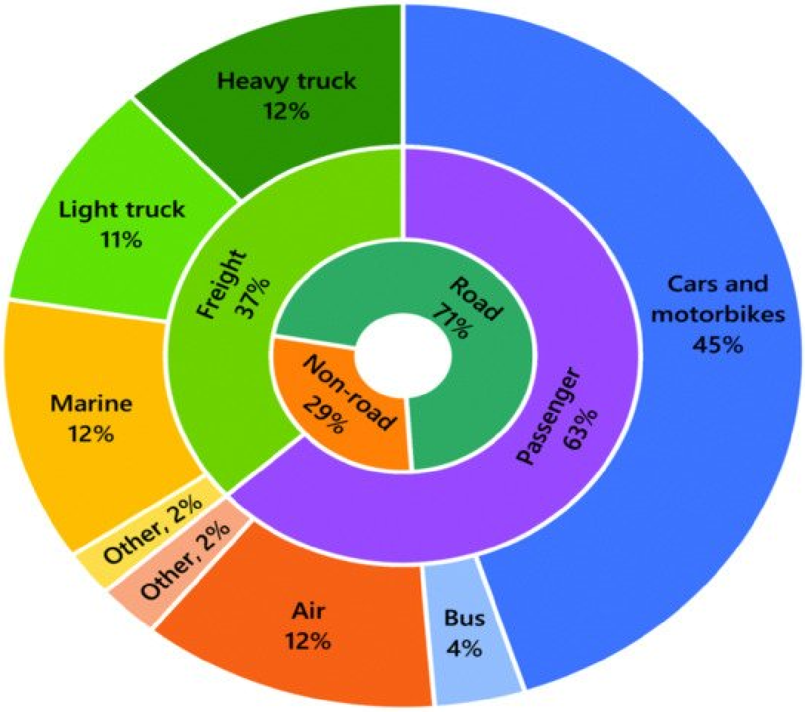

Figure 2. Summary of global energy utilization in the transport sector in 2015 [63][64].

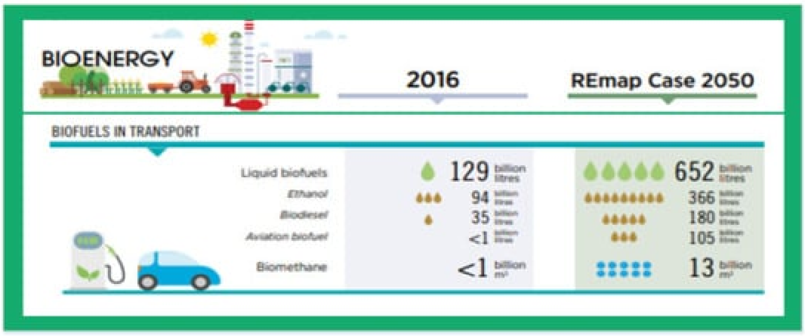

Figure 3. Biofuel in the transport sector, 2016 and 2050 scenarios. Adapted from [65]. Developed by the authors.

Liquid and gaseous biofuels are used to power ICEs. However, liquid biofuels are preferred over gaseous biofuels for vehicle propulsion. This is because liquid biofuels have a higher energy density than gaseous fuels, thereby allowing vehicles to possess immense range. **Table 2** shows the energy stored per liter for petrol or Petroleum-Based Gasoline (PBG) fuel, PBD fuel, and some biofuels. Gaseous fuels require pressurized tanks and they must be larger for an equal quantity of stored energy compared to liquid fuels. Also, refueling is more straightforward, easier, and faster with liquid fuels than gaseous fuels.

Table 2. Energy stored per liter of fuel [66].

Fuel	Stored Energy (MJ)
Diesel	**36**
Gasoline	**33**
Biodiesel	**33**
Methanol	**16**
Ethanol	**21**
Liquid H2 (at −253 °C)	**8.5**

Fuel	Stored Energy (MJ)
Compressed H2 (at 250 bar)	**2.5**

The use of a fuel as an ICE fuel depends on its properties. **Table 3** shows some properties of diesel, gasoline, and some liquid and gaseous biofuels. The density is calculated as the mass per unit volume. The density of a fuel is determined by the mass of fuel entering the combustion chamber and the air/fuel ratio. A Higher Heating Value (HHV) is the quantity of heat realized when a unit amount of fuel is completely combusted. HHV is obtained by cooling the products of combustion, leading to the formation of water vapor [67][68]. The HHV of fuel is directly proportional to the quantity of carbon in the fuel and the ratio of C-H to O2-N2. Conversely, the Lower Heating Value (LHV) of a fuel is the energy content of the fuel. The distinction between the HHV and LHV is a measure of the heat content of the condensed water vapor formed during combustion. The density and heating values determine the energy available in the fuel, along with the volume and mass. The Cetane Number (CN) is a function of the amount of time lag between the fuel injection and auto-ignition [67]. The CN is used to classify PBD fuel and measures the ability of the fuel to self-ignite. Fuels with high CNs are good for CI engines because this ensures that the engine enjoys an excellent start and runs smoothly, particularly during cold weather. A low CN tends to result in incomplete combustion and exacerbates the emission of dangerous gases [69].

Kinematic viscosity is a property that influences the atomization properties, the size of the droplets and spray penetration, and the potential of atomized fuel. Fuels with high kinematic viscosity values suffer from poor fuel atomization during the spray and increased wear rate of the engine, pump parts, and injectors, which jointly result in poor combustion and increased emissions [70]. Ethanol and dimethyl ether have lower viscosity values and are more capable of making fine droplet sprays than PBD fuel. The flash point measures the temperature at which sufficient water vapor is released to generate the appropriate quantity of the water vapor–air mixture and relates to the safe handling and transportation of the fuel. A fuel with a flashpoint below 38 °C (100 °F) is considered flammable [71]. The latent heat of vaporization quantifies the degree of coolness experienced as a result of fuel evaporation. The stoichiometric Air/Fuel ratio (A/F) of a fuel is a measure of the hydrogen/carbon ratio of the fuel and the quantity of oxygen contained in the compound [72]. The Research Octane Number (RON) is also used to classify PBG fuel and measures the ability of the fuel to self-ignite. High RONs are good for spark ignition (SI) engines [73]. The Reid vapor pressure is also a critical fuel fingerprint for measuring the behavior of fuel, particularly when the SI engine is appropriately carbureted and fueled. The ease with which the spark ignites the air/fuel mixture indicates the flammability limit of the fuel. Hydrogen fuel, a form of renewable fuel, is reputed to possess the highest flammability limit.

Table 3. Physical and chemical properties of some transportation fuels [66][74][75][76][77].

Property	PBG	PBD	Methanol	Ethanol	DME	Biogas	Hydrogen	Biodiesel	F-T Diesel
Chemical formula	**CnH1.87n**	**CnH1.8n**	**CH3OH**	**C2H5OH**	**CH3OCH3**	**CH4**	**H2**	**C15H31CO2CH3**	**C9 to C20**
Density (kg/m^3)	**720–780**	**820–870**	**800**	**790**	**667**	**-**	**70**	**850–885**	**774–782**
Kinetic viscosity at 40 °C (cSt)	**0.7**	**2.0–3.5**	**0.75**	**1.5**	**0.18**	**-**	**-**	**4.43**	**2-4.5**
Cetane number	**13–17**	**45–55**	**5**	**8**	**55–60**	**-**	**-**	**45-65**	**72**
Self-ignition temperature (°C)	**260[a]**	**210 [a]**	**470**	**365**	**320**	**580**	**500**	**220**	**315**
Lower heating value (MJ/kg)	**44**	**43**	**19.7**	**28.6**	**28.2**	**24**	**120**	**37**	**43.5 [a]**
Lower heating value (liquid) (MJ/L)	**33**	**36**	**16**	**21**	**19**	**-**	**8.5**	**33**	**-**
Higher heating value (mixture) (kJ/kg)	**3.8**	**3.9**	**3.5**	**-**	**3.4**	**3.1**	**2.0**	**-**	**-**

Property	PBG	PBD	Methanol	Ethanol	DME	Biogas	Hydrogen	Biodiesel	F-T Diesel
Adiabatic temperature (°C)	1995	-	1950	1965	2020	1954	2510	2000	-
Boiling temperature (°C)	25–210	180–360	65	78	−25	−162	−253	250–350	157.6
Reid vapor pressure at 38 °C (kPa)	55–100	<1.5	32	16	800	-	-	-	-
Stoichiometric A/F ratio	14.5 [a]	14 [a]	6.4	9.0	9.0	17	34.1	13 [a]	15
Research octane number	98	-	115	110	-	120	106	-	-
Enthalpy of vaporization (kJ/kg)	350 [a]	270 [a]	1100	900	375	510	455	-	-
Flammability limit (% vol.)	1.3–8	0.6–8	7–36	4.3–19	3.4–19	-	4–75	-	-
Flash point (°C)	-40	60–80	11	12	−41	-	-	62	500
Oxygen content (wt.%)	-	-	50	35	34.8	-	-	10.7	-
Carbon content (wt.%)	-	-	-	-	52.2	-	-	76.9	86.44
Hydrogen content (wt.%)	-	-	-	-	13	-	-	12.4	13.56

[a] Approximately. Compiled by the authors.

2.1. Utilization of Biofuels in Spark Ignition Engines

Generally, for a particular fuel to be suitable as a renewable alternative fuel for SI engine applications, it must meet the requirements for the octane number, flammability, combustion stability, the heating value of the air–fuel mixture, the laminar burning velocity, vapor pressure, the boiling curve, and volatility [78]. Against this backdrop, alternative fuels for SI engines can be categorized as either liquid biofuels or gaseous biofuels. Liquid biofuels include alcohols (methanol, ethanol, butanol) and gaseous biofuels include biogas and hydrogen. These are the preferred renewable alternatives to replace PBG fuel because of their advantages [60], which include: (i) higher octane numbers than PBG fuels; (ii) fewer olefins and aromatic-structured hydrocarbons than PBG fuels; (iii) lower sulfur content; (iv) higher flash points; (v) safer handling; (vi) better cold flow properties. Furthermore, bioethanol has a higher latent heat of vaporization compared to PBG fuels and alcohol fuels (oxygenated fuels) have (i) high oxygen content; (ii) lower Reid vapor pressure, resulting in lower emission of volatile organic components during filling at gas stations; and (iii) a lower carbon-to-hydrogen ratio than gasoline fuels, resulting in lower carbon-based emissions. However, there are some drawbacks to the use of these renewable alternatives, including [60]: (i) for alcohol fuels, lower calorific values compared to PBG fuels, resulting in lower power output, (ii) cold starting problems as a result of the high latent heat of vaporization values of renewable fuels, (iii) the oxygenated nature of the alcohol-based fuels, which leads to the generation of more NOx, although NOx emission is reduced due to the high latent heat of vaporization values of renewable fuels.

Biogas is used to power SI engines either as raw biogas or enriched biogas. Raw biogas is approximately 60% CH4 and roughly 40% CO2 with H2S, N2, and H2 in trace proportions [79]. Raw biogas suffers from lower flame velocities and calorific values when compared with gasoline fuel. SI engines fueled with raw biogas thus have poor combustion characteristics, lower thermal efficiency, higher specific fuel consumption, lower power output, and higher emissions of CO and HC because of the lower flame velocity, less adiabatic flame temperature, and lower calorific value of biogas compared to PBG fuels. To enhance the quality of the unrefined biogas, the CH4 content of the biogas can be enriched and the CO2, H2S, and water content reduced or removed. The upgraded biogas is called biomethane and possesses acceptable specifications for ICEs [80]. Various technologies and techniques have been successfully employed, at

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household and commercial scales, to upgrade and enrich biogas, including physical and chemical absorption, gas filtration, low-temperature separation, and various methods of scrubbing [81][79][80][82][83][84].

Hydrogen, which has been used in the hydrocracking of petroleum products, ammonia production, the heat-treating and refining of metals, the catalytic hydrogenation of organic compounds, fertilizer production, glass purification, and other applications, has also found uses as an alternative fuel for SI engines as part of emission mitigation strategies. An estimated 120 million tons of hydrogen, equivalent to 14.4 EJ, are produced annually, with about 95% produced from fossil fuels (natural gas and coal) and the remaining 5% generated by the electrolysis process [85]. Various technologies have been deployed for the production of hydrogen to meet its growing demand. Photochemical, thermochemical, and electrochemical methods are the three main technologies that have been employed for the production of hydrogen from various sources [86]. Fuel hydrogen is also generated using biological routes, including direct and indirect bio-photolysis and dark fermentation and photofermentation with organisms like cyanobacteria and green algae [87]. Sharma and Ghoshal [88] surveyed various technologies for hydrogen fuel production, including steam methane reforming, gasification of coal, electrolysis of water, and technologies using biomass and nuclear energy. The application of hydrogen as a substitute fuel for SI engines has been reported by various researchers [89][90].

Bioethanol is one of the most prominent biofuels because of its easy production method and the use of native and readily available raw materials as feedstocks. Bioethanol is produced through the fermentation of various raw materials including sugarcane, molasses, sugar beet, sweet sorghum, rice, potato, sweet potato, barley, and fruit and vegetable waste. Fermentation is a biochemical process for the anaerobic conversion of the simple sugars obtained from hydrolysis of lignocellulosic biomass into bioethanol. The process of conversion of lignocellulosic biomass into simple sugars is a complicated procedure due to the existence of long-chain polysaccharide molecules, and it therefore demands acids or enzymes.

There are three types of microorganisms frequently utilized for the conversion of lignocellulosic biomass to bioethanol: yeasts, bacteria, and fungi. Yeasts have proven to be the best microorganism for fermentation of biomass to bioethanol. In particular, the yeast Saccharomyces cerevisiae, operating at a temperature of 30 °C, pH 5.5, and with a fermentation time between 48 h and 56 h, resulting in an ethanol yield of 130.13 g/L [91], and the bacterium Zymomonas mobilis, operating at a temperature of 30 °C, pH 6.0, and with a fermentation time of 18 h, resulting in an ethanol yield of 99.78 g/L [92], have been used for commercial production of ethanol.

2.2. Utilization of Biofuels in Compression Ignition Engines

Compression ignition (CI) engines have better thermal efficiency than SI engines and have found applications in diverse areas, including transportation, construction, agriculture, and power generation. The need for renewable fuel to power CI engines results from the poor performance and hazardous emissions, particularly of CO, UHC, NOx (NO and NO_2), and PM, of CI engines fueled with PBD fuel. The selection of fuels for CI engines is based, primarily, on the cetane number of the fuel. A fuel candidate for CI engines must meet some important criteria, namely [78]: a good cetane number, appropriate boiling point, a narrow density and viscosity spread, and low aromatic compound content. Such fuel must ensure quality ignition, combustion without knock, and smooth running of the engine. Biodiesel, Fischer–Tropsch (F-T) fuel, and dimethyl ether (DME) are the preferred renewable fuels for CI engines because of their higher cetane numbers and lower levels of olefins and aromatic-structured hydrocarbons compared to PBD fuels. Furthermore, biodiesel and F-T fuels have higher flash points than PBD fuels, but F-T and DME fuels have better cold flow properties than biodiesel.

Biodiesel and its blends have been used to power CI engines due to their characteristic oxygenated fingerprints, which support complete combustion. Though the combustion, performance, and emissions characteristics of biodiesel as a CI engine fuel have been studied, the determining factors that have engaged the interest of researchers are the improved performance and mitigated emissions characteristics of unretrofitted engines fueled with biodiesel. Over the years, biodiesel has been produced from various feedstocks and the products have been tested and compared with PBD fuel using the BSFC, BTE, BP, and EGT as performance criteria and measurement of NOx, PM, UHC, and CO emission benchmarks. The ultimate goal is to make biodiesel-fueled CI engines consume less fuel, generate more power, and emit less hazardous gases [60][93]. Biodiesel, due to its increased oxygen content, has low calorific values and consequently emits more NOx emissions and suffers from power drops.

F-T diesel is produced through a catalytic chemical reaction where syngas derived from biomass are converted into hydrocarbons of various molecular weights. The reaction takes place at a temperature range of 200–350 °C and pressure range of 300–600 psi. The Fischer–Tropsch process is a catalytic exothermic reaction that can take place in a fixed bed, fluidized bed, or slurry bed reactor in the presence of iron, cobalt, or nickel catalysts [87][88].

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F-T diesel has a higher calorific value, higher cetane number, and lower density than PBD fuel. F-T diesel fuel contains more paraffinic compounds, has a lower C/H ratio, lower in-cylinder temperature, lower aromatic or sulfur content, and better combustion properties, resulting in lower NOx, UH, CO, and PM emissions in comparison with PBD fuel. F-T diesel has better cold flow properties and superior transportation and storage properties when compared with biodiesel. F-T diesel-fueled CI engines emit less NOx and suffers from fewer power drops, making F-T diesel a better renewable fuel than biodiesel for CI engine applications [94].

Dimethyl Ether (DME) a clean, colorless, non-toxic, and degradable gas, which was originally applied as an aerosol propellant and in LPG blending for cooking, has become a prominent alternative to FB fuels. Currently, there is large-scale production of DME in many countries, including Argentina, Brazil, Canada, China, India, Japan, Mexico, Russia, South Korea, Sweden, the USA and Uzbekistan. According to the International DME Association, current global production is about 9 million tons per annum, while the global market size, which was USD 5.6 billion in 2020, has been projected to reach USD 9.7 billion in 2027 [95][96].

DME can be produced from biomass, coal, municipal waste, natural gas, methanol, agricultural bio-products, and other bio-based feedstocks through either direct or indirect routes. In the indirect production route, methanol is hydrogenated from syngas and the product is purified and dehydrated. Direct synthesis of DME is achieved in a single-stage process directly from syngas in an exothermic reaction [85]. Inayat et al. [86] investigated the use of an empty fruit bunch as feedstock to synthesize DME in a production process that involved gasification, waster-gas shift reactions, and CO2 removal. Partial oxidation, gasification, Boudouard, methanation, and methane-reforming reactions take place during the gasification stage. The schematic diagram of the production process is shown in **Figure 4** [86].

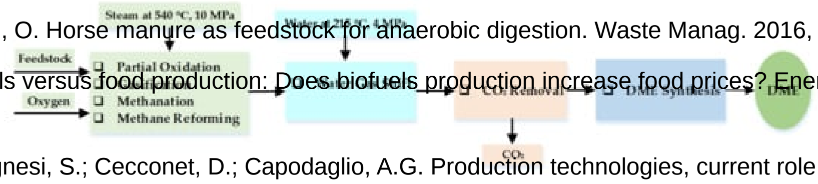

Figure 4. Schematic diagram of the DME production process. Adapted from [77]. Developed by the authors.

As a result of its many applications, the global DME market, appraised at USD 4790 million in 2017, is projected to reach USD 9100 million in 2024 [95]. DME as a CI engine fuel discharges low NOx, SOx, and soot emissions and has outstanding combustion attributes [96]. The choice of DME (CH3OCH3) as a sustainable fuel for CI engines is strengthened by its superior oxygen content, which allows better combustion and lower NOx, UHC, and smoke emissions, higher cetane numbers, and shorter ignition delays than PBD fuel. The emission of less smoke and PM can also be attributed to the lack of C-C bonds, as DME has only C-H and C-O bonds. DME-fueled CI engines offer the best emissions when compared with biodiesel and F-T diesel, but its utilization as a vehicle fuel and its adoption for vehicle fleets is hampered by the lack of production, storage, transport, and dispensing infrastructures. Also, DME has lower lubricity, resulting in increased wear of moving parts; lower viscosity, which can cause leakages in fuel pumps and fuel injectors; and higher flammability limits than PBD fuel [60][94][97]. **Table 4** shows data on biodiesel, F-T diesel, and DME-fueled CI engines in terms of their performance and emission characteristics.

Table 4. Effects of biodiesel, F-T diesel, and DME as alternative fuels for CI engines.

Biofuel Used	Engine Details	Effects		Ref.
		Performance	Emissions	
Biodiesel	1C, 4S, NA, DI, air-cooled	• ↑BSFC • ↓BTE	• ↑CO, CO2, NOx, • ↓HC, SO	[98]
Biodiesel	1C, common-rail DI, r = 16	• ↑BTE • ↓BSFC	• ↑SO, CO, UHC • ↓NOx	[99]

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Biofuel Used	Engine Details	Effects: Performance	Effects: Emissions	Ref.
Biodiesel	1C, 4S, DI, VCR, water-cooled	• ↑BTE, BSFC, EGT • ↓BP	• ↑NOx • ↓UHC, CO, SO	[100]
Biodiesel	2C, water-cooled, r = 17.5, N = 1500 rpm	• ↑BTE, BSFC, EGT • ↓BP	• ↑CO2, NOx, SO • ↓CO, UHC	[101]
Biodiesel	1C, 4S, constant speed, water-cooled	• ↑4.2% BSFC • ↓10.8% BP, 3.6% BTE	• ↑CO2, NOx • ↓CO, UHC, SO	[102]
DME	1S, common rail injection	• ↑IMEP	• ↑NOx, • ↓HC, CO • Almost zero soot	[103]
DME	1S, 4S, DI, water-cooled, r = 18, N = 2200 rpm	NA	• ↓CO, HC, NOx	[104]
DME	4C, NA, in-line, common rail, r = 18.5	• ↑BSFC • ↓BTE, EGT	• ↑NOx, HC, CO	[105]
DME	1S, common rail, r = 16.7	• ↑BSFC, BTE • ↓EGT	• ↑NOx • ↓CO, HC, PM	[106]
F-T	1S, 4S, NA, DI, water-cooled, r = 18	• ↓BSFC	• ↓CO, CO2, HC, NOx, SO	[107]

↑ = increased, ↓ = reduced, DI = direct injection, EGT = exhaust gas temperature, VCR = variable compression ratio, SO = smoke opacity, C = cylinder, N = engine speed, NA = naturally aspirated, S = stroke, IMEP = indicated mean effective pressure, Vs = swept volume, r = crank radius, BP = brake power, BTE = brake thermal efficiency, BSFC = brake specific fuel consumption.

3. Implications

Biofuels have been widely accepted as alternative fuels for the transportation sector to enhance the performance of transport vehicles. The challenges associated with the application of FB fuels as ICE fuels include operational, performance, safety, cost, infrastructure, and durability challenges. The conversion of various categories of waste into useful fuels has become advantageous in terms of economic, sanitation, availability, and environmental considerations. The choice of feedstock, conversion technology, production infrastructure, and utilization platform cannot be restricted to fuel producers and engine manufacturers but must involve professionals from many disciplines, including finance, plant science, microbiology, chemical engineering, mechanical engineering, process engineering, environmental science, food science, agronomy, and more. Investigations into areas such as metabolic engineering, processing subsidizations, tax immunity, feedstock identification, equipment development, engine modifications, land use regulations, and the use of artificial intelligence, are needed to ensure the sustainable production and application of biofuels [108][109][110]. Political leaders from various jurisdictions, policymakers, funders, investment analysts, and other development partners must unite in making biofuel production and utilization worthwhile and sustainable.

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