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Biodiesel Plants

Fueling the Sustainable Outlooks

Edited by Eduardo Jacob-Lopes, Leila Queiroz Zepka and Mariany Costa Deprá

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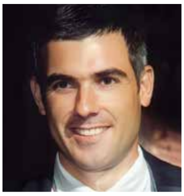
Meet the editors



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Contents

Preface

In an era where the urgency of securing a sustainable energy future becomes increasingly evident, clean and renewable alternatives emerge as beacons of hope, illuminating the path to preserving our ecosystem. Among these solutions, biodiesel stands out as a promise of liberation from the destructive impacts of fossil fuels, representing the possibility of a more just and balanced reality. However, like all great innovations, the journey toward its full implementation is fraught with challenges and obstacles. Technological bottlenecks still obscure the vast transformative potential of this bioenergy source. Thus, as time relentlessly progresses, pursuing energy security and independence remains a continuous, urgent, and necessary challenge.

Within this context, *Biodiesel Plants – Fueling the Sustainable Outlooks* seeks to explore the technological innovations aimed at transforming biodiesel into a pillar of our energy future. By looking into the latest scientific advancements, this book reveals the ongoing progress required to make biodiesel a viable, effective, and essential solution in a world thirsty for sustainable alternatives. Each chapter, like an open window to the future, unveils the biodiesel production process, from the careful selection of feedstocks to the innovative technologies reshaping the energy industry's future. With a keen focus on sustainability, the book highlights advancements that reduce the environmental impacts of biodiesel production and foster a greener and more resilient economy.

The content presented here is directed at scientists, engineers, and policymakers in renewable energy, inviting them on a journey of discovery and inspiration. We hope the ideas and reflections shared within this book will inspire new research pathways, fueling the pursuit of a new threshold for sustainable energy.

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Chapter 1

Introductory Chapter: Sustainable Freedom in Biodiesel Plants – Insights about a Society Dependent on Fossil Fuels

Mariany Costa Deprá, Leila Queiroz Zepka and Eduardo Jacob-Lopes

1. Introduction

Fossil fuels changed the course of history. Under a brief comparative lens, it is clear that the current world is unrecognizable from the beginning of the nineteenth century before these were widely used. As we know, fossil fuels not only drove the Industrial Revolution, agriculture, and transport, but also led to marked improvements in health, well-being, and the reduction of population poverty, becoming the lifeblood of the global economy and shaping modern society [1].

During the last few centuries, it seemed like a great idea to use solar energy concentrated and stored over millions of years rather than relying on solar flows and biomass. However, as we evolved, the interactions of a substantially larger and more integrated global economy required much greater energy quantities to satisfy our needs. Thus, the longevity of fossil substances was often questioned, and their depletion was seen as an increasing concern [2].

Thus, for a long time, it was believed that fossil fuel reserves were ready to pull the plug. As we used more and more available oil and its co-derivatives, reserves would decrease. Consequently, the premise was established that we would need to switch to renewable energy sources when fossil reserves had extremely low limits. However, we had not realized that as scientific advances gained new technological readiness-level maturity, more reserves would be found and more resources extracted. Furthermore, what we did not expect was that the advantages of exploring new reserves would present a devastating disadvantage [3].

Unfortunately, we belatedly understood that the carbon dioxide released from its burning was harming our planet faster than anything we had seen in the geological records. Therefore, one of the biggest hurdles humanity is facing is to alleviate this environmental imbalance before it changes our world beyond recognition [4]. Thus, simply waiting for the depletion of fossil reserves to then promote the renewable energy transition has become an imminent wait for potential catastrophic events; after all, there is no room for sustainability when it comes to fossil resources.

Given this scenario, measures were designed to stop the environmental collapse. Among them, the consensus not to exhaust proven reserves and, if plausible, to make probable and possible reserves intangible encouraged the search for renewable substitutes. In this context, during the last two decades, researchers have focused on several key aspects to boost the development of renewable and clean fuels, such as biodiesel. Since then, biodiesel has been recognized as a valuable resource for the global energy sector [5].

Biodiesel production has become increasingly popular among the various fossil fuel substitutes. This is because its physical-chemical characteristics are comparable to that of oil, such as its calorific value, viscosity, density, and volatility, characteristics that are fundamental to ensuring its quality. Besides, biomass-based biodiesel has advantages over its non-renewable counterpart, due to its common reduction in carbon dioxide emissions. Furthermore, the versatility of raw materials to be used makes it an attractive, renewable, and potentially sustainable bioresource [6]. Therefore, increasing biodiesel in the bioenergy sector through renewable biomass use can help improve energy balance and decrease dependence on fossil fuels in the contemporary landscape [7].

On the other hand, despite its potential viability, the conventional biodiesel manufacturing system is often interrupted by uncontrollable production problems that affect the long-term results of procedures, which makes it necessary to look at the smart remanufacturing strategy [7]. Among them, issues associated with energy efficiency, storage stability, infrastructure, and distribution are addressed, as aspects related to compatibility with equipment and engines. Furthermore, biomass use from food crops to produce biodiesel can lead to a shortage of biomass for human use and, consequently, drive food price inflation [2]. Therefore, to meet growing demand and effectively guarantee sustainability, it is vital to review and update technological strategies to speed up the industrial synthesis of biodiesel [5].

In parallel, alongside science, engineering, and technology challenges, political nature interactions make the energy transition—led by biodiesel—a difficult breakthrough to achieve. On the one hand, science tells us that we need to remake our energy system; on the other, minimizing the impact of climate change requires the reconstruction of a multimillion-dollar industry that is at the center of the economy and people's lives. Therefore, reducing humanity's dependence on fossil fuels requires investments here and now that provide uncertain, long-term benefits. These decisions are particularly difficult for a society that tends to focus on policies with immediate benefits [8]. On the face of it, the substantial transitions triggered by biodiesel production not only embrace a deeper reworking of energy technologies and the economy but also the physical and human geographies, social communities, and energy political structure for production, distribution, and consumption [9, 10].

2. Final remarks

The starting point for biodiesel consolidation is to recognize that just the argument for the energy transition will not be enough. We must consider that this process requires the interconnection of multiple factors, which are sometimes controversial and heterogeneous. However, with the growing academic and public interest in sustainable bioenergy resources, it is essential to build up a more systematic epistemological structure to better acknowledge the driving forces and outcomes of the biodiesel plants as a leading bioresource. Therefore, the role of researchers from academia and key decision-making actors in the industrial sectors is to ensure that transformative connections are formed between innovative know-how and the international industry community to create meaningful strategies, insights, and practical actions to drive and fuel the sustainable outlooks of biodiesel plants.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this chapter.

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Chapter 2

Understanding Biodiesel: From Feedstock to Fuel

Fayaz A. Malla, Afaan A. Malla, Showkat Rashid, Nazir A. Sofi and Mukhtar Ahmed

Abstract

Biodiesel has evolved as a viable and environmentally friendly substitute for traditional diesel fuel derived from petroleum. Biodiesel is a fuel that is produced from many sources such as vegetable oils, animal fats, and cooking oil. It provides a cleaner and more eco-friendly alternative for transportation and other energy requirements. This chapter delves into the complexities of biodiesel, covering its manufacturing methods, selection of raw materials, fuel characteristics, uses, and economic and environmental factors to be considered. The book chapter analyses the chemical conversion of feedstock into biodiesel using transesterification, investigating several techniques and their influence on the quality of the fuel. The analysis focuses on important fuel characteristics, including cetane numbers, cold flow, and oxidative stability, and how they affect engine performance and emissions. Moreover, it examines the economic feasibility of producing biodiesel, considering government subsidies, production expenses, and market dynamics. The environmental advantages of biodiesel are emphasized, such as its capacity to decrease greenhouse gas emissions, enhance air quality, and alleviate reliance on fossil fuels.

Keywords: transesterification, renewable fuel, energy security, sustainable alternative, greenhouse gas emissions

1. Introduction

Biodiesel, an ecologically viable and environmentally preferable alternative to conventional diesel fuel, is increasingly being acknowledged as the international community strives to mitigate environmental damage and reduce reliance on fossil fuels [1]. To fully understand biodiesel, it is necessary to carefully analyze its definition, historical development, distinguishing characteristics compared to traditional diesel, environmental implications, challenges in manufacturing, and its significant role in advancing sustainability in the energy industry. Biodiesel is a type of biofuel that is produced by the process of transesterification, using natural oils derived from plants such as soybean, canola, or palm, as well as animal fats [2]. This process involves the reaction of oils or fats with alcohol, usually methanol or ethanol, in the presence of a catalyst to produce fatty acid methyl or ethyl esters, often known as biodiesel, and glycerine as a secondary product. The biodiesel produced is compatible with diesel engines without requiring any modifications, facilitating a seamless transition from conventional petroleum-based diesel fuel [3, 4].

When comparing the qualities of biodiesel and regular diesel, numerous distinctions arise. Biodiesel exhibits exceptional lubricity, resulting in reduced engine friction and prolonged engine longevity [5]. Additionally, it possesses a greater cetane number, which enhances the efficiency of combustion and reduces emissions of nitrogen oxides (NO_x). The reduced sulfur content of biodiesel helps to minimize the release of sulfur dioxide (SO_2), which is a major air pollutant. The higher viscosity and lower energy content of biodiesel in comparison with petroleum diesel could potentially result in a small reduction in both fuel economy and power output [6].

Biodiesel offers significant environmental advantages in comparison with conventional diesel fuel. Biodiesel is derived from renewable sources, hence reducing reliance on finite fossil fuel reserves and mitigating greenhouse gas emissions [7]. Biodiesel production often requires less energy and generates lower amounts of greenhouse gas emissions compared to conventional diesel refining techniques. Ensuring sustainable production methods is crucial in addressing concerns over changes in land usage, particularly in relation to the cultivation of biodiesel feedstock [8, 9].

2. Feedstock for biodiesel production

2.1 Exploring different types of feedstocks

Biofuels have garnered considerable interest as a substitute for fossil fuels owing to its capacity to diminish greenhouse gas emissions and reliance on finite resources. An essential factor in the manufacture of biofuels is the careful choice of suitable feedstock. The feedstock usually utilized in biofuel production encompasses a range of materials, including vegetable oils (such as soybean, canola, and sunflower), animal fats, leftover cooking oil, and algae.

Soybean, canola, and sunflower oils are common ingredients in biodiesel because of their high oil content and beneficial fatty acid composition. The principal feedstock for biodiesel in the United States is soybean oil, which contains 18 to 20% oil [10]. Canola oil, made from rapeseed, is preferred because it has a high concentration of monounsaturated fats and a low concentration of saturated fats, which improve the quality of the fuel [11]. The oil content of sunflower oil makes it beneficial; however, its availability and cost can vary by region [12]. Tallow, lard, and other animal fats are used as feedstocks for biodiesel, but they pose problems in terms of quality control [13, 14]. A cleaner option used cooking oil (UCO) needs to be treated first to remove contaminants [15, 16]. Also, there are scalability issues with algae, yet they could be used as biofuel feedstocks [17, 18].

2.2 Sustainability considerations for feedstock selection

In biofuel production, the feedstock choice has a significant impact on the long-term viability of the product from financial, environmental, and social perspectives. Alternating with food crops and using less fertile land are two ways sustainable feedstocks reduce land use conflicts including deforestation and habitat degradation [19]. The loss of biodiversity can occur as a result of land-use changes caused by feedstock farming, which can release carbon and alter ecosystems [20]. Improving water efficiency and reducing contamination hazards are crucial concerns due to the high water requirement of certain feedstocks, such as algae [21]. According to Tilman et al. [22], sustainable feedstocks should reduce emissions of greenhouse gases at every stage of their lifespan. Using non-food feedstocks and staying away from delicate habitats are two further ways to preserve biodiversity [23]. Last but not least, people should think about how biofuel initiatives will affect things such as food security, labour standards, and property rights to make sure the community benefits [24].

2.3 Impact of feedstock on biodiesel properties

Biodiesel is made from a variety of feedstocks that affect its cold flow properties, oxidative stability, cetane number, and viscosity; these qualities make it a greener alternative to conventional diesel. Biodiesel made from vegetable oils, such as soybeans, typically has a lower cetane number than biodiesel made from animal fats, because of the changes in the makeup of fatty acids [25]. The increased cetane values and improved ignition characteristics of biodiesel made from animal fat are a result of the higher saturated fat content [26]. Biodiesel derived from oils with longer chain lengths, such as soybeans, has a higher kinematic viscosity than biodiesel derived from oils with shorter chain lengths, such as palm oil [27]. Biodiesel made from algae has the potential to be less viscous, making it more appropriate for use in colder areas [17]. According to Lin et al. [15], pre-treatment of used cooking oil (UCO) biodiesel can enhance its oxidative stability, which is vital for avoiding fuel degradation. The cold flow characteristics of canola biodiesel are improved by its high monounsaturated fat content [11].

2.4 Advances in feedstock development and processing

Improving sustainability, efficiency, and economic viability is crucial for meeting the increasing demand for biodiesel, which in turn requires breakthroughs in feedstock development and processing technology. Biodiesel crops with improved oil yield and biodiesel-friendly fatty acid composition have been developed by genetic engineering in plants such as canola, algae, and soybeans [28]. Biodiesel lipid synthesis has also been enhanced through metabolic engineering of microorganisms such as bacteria and yeast [29]. The manufacture of biodiesel has become more efficient and eco-friendly thanks to catalyst design developments and catalytic conversion methods such as hydroprocessing and transesterification [30]. Gong et al. [31] found that supercritical fluid technologies can produce high-quality biodiesel with faster reactions and less solvent use. Biddy et al. [32] and Ghavipour et al. [33] found that integrated biorefineries improve economic and environmental sustainability by optimizing feedstock and producing biodiesel alongside important by-products such as biochar and bio-based chemicals.

3. Biodiesel production processes

3.1 Transesterification: The core process of biodiesel production

Transesterification is the essential chemical process used in the production of biodiesel. It involves the conversion of triglycerides, which are present in oils and fats used as raw materials, into fatty acid methyl esters (FAMEs), which are the main components of biodiesel. This procedure entails the interaction of triglycerides with alcohol, commonly methanol or ethanol, in the presence of a catalyst to produce biodiesel and glycerol as a secondary product [26, 34].

3.1.1 Mechanism of transesterification

Transesterification is a chemical process where alkyl groups are swapped between triglyceride molecules and alcohol molecules. The reaction proceeds in three steps:

a. Formation of alkoxide ion: The alcohol molecule is deprotonated by the catalyst (usually a base or acid) to form an alkoxide ion.

b. Attack of triglyceride: The alkoxide ion attacks the carbonyl carbon of the triglyceride, leading to the formation of an intermediate complex.

c. Formation of fatty acid methyl esters (Biodiesel): The intermediate complex decomposes to yield fatty acid methyl esters (FAMEs) and glycerol.

Transesterification is commonly carried out at high temperatures, typically between 50 and 70°C, in order to expedite the rate of the reaction [6, 9, 15, 16, 33].

3.1.2 Catalyst

Catalysts, such as alkali or acid catalysts, are necessary to facilitate the transesterification reaction. Alkali catalysts, such as sodium hydroxide or potassium hydroxide, are frequently employed because of their elevated reactivity and specificity. Alkali catalysts, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), are commonly employed in transesterification reactions because of their significant catalytic efficiency and comparatively affordable price [6, 28, 30, 34].

3.2 Understanding the chemistry behind transesterification

Transesterification is a chemical process where the ester groups within a molecule are replaced with alkyl or other ester groups from a different molecule. Transesterification, in the context of biodiesel manufacturing, is the process of transforming triglycerides that are often present in vegetable oils or animal fats, into fatty acid alkyl esters (also known as biodiesel) and glycerol. The general chemical equation for transesterification can be represented as follows:

$$\text{Triglyceride} + \text{Alcohol} \rightarrow \text{Biodiesel} + \text{Glycerol} \tag{1}$$

3.2.1 Formation of alkoxide ion

The transesterification reaction commonly initiates with the deprotonation of the alcohol molecule by a catalyst, which can be either an acid or a base, resulting in the formation of alkoxide ion. For instance, if methanol (CH_3OH) is employed as alcohol, the reaction can proceed in the following manner.

$$CH_3OH + \text{NaOH} \rightarrow CH_3\text{O}^- Na^+ + \text{H}_2\text{O} \tag{2}$$

3.2.2 Nucleophilic attack

Alkoxide ion functions as a nucleophile by attacking the carbon atom of the triglyceride molecule. Triglycerides are composed of three fatty acid chains that are bonded to glycerol. The nucleophilic attack takes place at the ester bond, causing one of the fatty acid chains to be replaced. This process results in the creation of an intermediate compound called acylglycerol. The acylglycerol intermediate consists of a single fatty acid chain connected to the glycerol backbone, while the remaining two sites are unoccupied.

$$CH_3\text{O} - Na + +\text{Triglyceride} \rightarrow \text{Acylglycerol} + \text{NaOH} \tag{3}$$

3.2.3 Acyl migration

Subsequently, the alkoxide ion originating from another alcohol molecule initiates an attack on the acylglycerol intermediate, resulting in the transference of the fatty acid chain from glycerol to the alcohol molecule. This procedure leads to the creation of a fatty acid alkyl ester, often known as biodiesel, as well as monoacylglycerol.

$$\text{Acylglycerol} + CH_3OH \rightarrow \text{Fatty Acid Alkyl Ester} + \text{Monoacylglycerol} \tag{4}$$

3.2.4 Completion of transesterification

The transesterification process proceeds until all triglyceride molecules are transformed into biodiesel and glycerol. The glycerol generated in the reaction is commonly isolated from the biodiesel using a purification procedure.

3.3 Different methods of transesterification

The transformation of triglycerides into biodiesel and other fatty acid alkyl esters is known as transesterification. Biodiesel and glycerol are produced in the most prevalent process, base-catalyzed transesterification, by speeding up the reaction of triglycerides with alcohol using an alkaline catalyst such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). Although it is slower and less effective than the base-catalyzed approach, acid-catalyzed transesterification is helpful for specific feedstocks because it uses acids such as sulfuric acid (H2SO4) to improve reactivity with alcohol. Although lipase-enzymatic transesterification provides mild reaction conditions and excellent selectivity, the cost of the enzymes is a limiting factor. While supercritical fluids, such as CO_2, improve reaction speeds and selectivity in transesterification, they also necessitate costly apparatus. Researchers are always looking for new catalysts and technology to make biodiesel production more efficient and environmentally friendly, but each approach has its own set of pros and cons.

3.4 Process variables and optimization

Improving product quality, enhancing biodiesel yield, and minimizing costs all depend on optimizing the transesterification process. Optimizing the alcohol-to-oil ratio to guarantee complete triglyceride conversion with little waste and reaction temperature, where higher temperatures speed up the process but may lower selectivity, are key considerations. Common base catalysts include NaOH or KOH, and their concentration has a major impact on reaction speed and product purity. Optimizing reaction times maintains a balance between complete conversion and unnecessary extension of reaction durations. Biodiesel synthesis often faces the problem of soap formation; however, this can be prevented by managing the water concentration and mixing the reactants with the appropriate intensity. Last but not least, centrifugation and distillation are essential purification procedures for obtaining useful by-products and eliminating contaminants [27]. Sustainable and economically viable biodiesel production can be achieved by effective management of these aspects in conjunction with ongoing research.

3.5 Biodiesel production technologies and equipment

Technologies for producing biodiesel range from simple to complicated, scalable, and efficient, meeting the needs of manufacturers on a small or large scale. Centrifuges and other separation devices separate biodiesel from glycerol in batch transesterification, which comprise reactor vessels for the chemical reaction, agitation devices for mixing, and heating systems for regulating temperatures. Şanlı and Çanakçı state that continuous flow systems include reactors like stirred-tank or tubular kinds, which necessitate pumps to maintain a constant flow of feedstock and heat exchangers to regulate temperature. Separation units, such as distillation columns, are also used in these systems. The use of cavitation and turbulence created by ultrasonic waves speeds up the transesterification process; this method typically necessitates the regulation of temperature and the use of conventional separation equipment. Relying on pressure management systems to maintain supercritical conditions and separation units for recovery, supercritical fluid transesterification utilizes supercritical fluids such as CO_2 or methanol to improve mass transfer. Purification equipment is needed to separate biodiesel and recycle enzymes in enzymatic transesterification, which uses lipases and other enzymes in reactors that are mixed and have temperature control to optimize conditions [27]. The industry is constantly evolving due to new technical advances; as a result, emerging hybrid and advanced process designs strive to increase efficiency, decrease costs, and guarantee sustainability.

4. Biodiesel applications and blending

4.1 Direct use of biodiesel in diesel engines

The utilization of biodiesel in diesel engines has attracted considerable interest as a substitute for traditional diesel fuel, owing to its environmental advantages, renewable nature, and capacity to decrease reliance on fossil fuels. Biodiesel, which is produced from vegetable oils, animal fats, or recycled cooking oils, can be utilized either in its pure form (B100) or mixed with petroleum diesel in different ratios. Although biodiesel has many benefits, its utilization in diesel engines poses certain difficulties that must be resolved to guarantee optimal performance and durability of the engine.

Diesel engines are specifically engineered to operate on diesel fuel, which possesses distinct characteristics such as high energy density, effective lubrication, and stability throughout a broad spectrum of operating circumstances. Biodiesel, although comparable, varies in some crucial aspects. Direct use of biodiesel in diesel engines can have an impact on engine performance due to variations in energy content, viscosity, and combustion properties. Biodiesel often possesses a diminished energy level in comparison with traditional diesel fuel. Biodiesel has a lower energy density, resulting in a somewhat inferior fuel economy and power output due to the reduced energy per unit volume. Biodiesel generally possesses approximately 10–12% lower energy content compared to petroleum diesel. Consequently, if the engine is not appropriately modified to account for this disparity, it may experience a corresponding reduction in performance.

An important obstacle related to the direct utilization of biodiesel in diesel engines is its performance in low temperatures. Biodiesel exhibits elevated cloud and pour points compared to regular diesel, indicating its tendency to solidify at higher temperatures. This characteristic can result in the obstruction of the fuel filter and problems with the movement of gasoline in low-temperature environments, which may potentially result in difficulty starting the engine and operating challenges. In order to address the problems caused by cold weather, it is common to utilize biodiesel mixes, such as B20 (which consists of 20% biodiesel and 80% petroleum diesel), instead of pure biodiesel (B100). By combining biodiesel with regular diesel, the fuel's cloud and pour points are reduced, enhancing its capacity to function in cold weather conditions. In addition, the utilization of cold flow improvers and heating components in fuel systems can effectively address the difficulties related to the elevated gel point of biodiesel.

Utilizing biodiesel in diesel engines can have a substantial effect on emission profiles. Biodiesel is recognized for its environmental advantages that encompass reduced emissions of particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC) in comparison with traditional diesel fuel. The decrease in emissions is mainly attributed to the elevated oxygen concentration in biodiesel, which facilitates enhanced combustion efficiency. Research has demonstrated that the use of biodiesel can effectively decrease particulate matter (PM) emissions by up to 50% and carbon monoxide (CO) emissions by approximately 30%. The decrease in particle matter (PM) is especially advantageous for the quality of air in metropolitan areas and the well-being of the people, as particulate matter is a recognized respiratory irritant and has been associated with a range of health problems. Nevertheless, the utilization of biodiesel might result in a rise in nitrogen oxide (NOx) emissions, which serves as a precursor to the formation of smog and acid rain. Biodiesel's greater cetane number and oxygen concentration can increase combustion temperatures, which in turn can enhance the generation of NOx. Modifying the engine's performance, such as fine-tuning the timing of fuel injection, and implementing NOx reduction technologies like selective catalytic reduction (SCR) systems, can effectively control and reduce these emissions.

4.2 Biodiesel blends with conventional diesel (B2, B5, B20, etc.)

Biodiesel, a renewable substitute for traditional diesel fuel, has been created as a result of the pursuit of environmentally friendly and long-lasting energy sources. It is obtained from vegetable oils or animal fats. Biodiesel blends, which involve the combination of a portion of biodiesel with traditional diesel, present a hopeful avenue for diminishing dependence on fossil fuels and decreasing the release of greenhouse gases. The blends, also referred to as B2 (2% biodiesel), B5 (5% biodiesel), B20 (20% biodiesel), and similar designations, offer a range of choices for incorporating bio-based fuels into the current infrastructure. B2 blends, which are widely used in many countries, provide a low-impact introduction to biodiesel, causing little effect on engine performance and compatibility. They facilitate a progressive transition to sustainable fuels, enabling the gradual establishment of infrastructure and adoption by consumers. B5 blends, despite having a greater proportion of renewable material, remain compatible with the majority of diesel engines, striking a harmonious balance between environmental advantages and usability.

B20 blends necessitate a greater degree of infrastructural modification, representing a substantial advancement in the utilization of renewable fuel. Although diesel engines can significantly reduce greenhouse gas emissions, certain adjustments or modifications may be necessary to achieve optimal performance. B100, a type of biodiesel that is completely pure, has the largest amount of renewable fuel. However, it can only be used with specific engines and infrastructure. It is primarily in the experimental stage, facing difficulties in terms of performance in cold weather conditions and storage for extended periods of time.

4.3 Engine compatibility and performance with biodiesel

Biodiesel blends, although providing a more environmentally friendly option compared to traditional diesel, necessitate meticulous evaluation of engine compatibility and performance. The crucial determinant is the proportion of biodiesel in the mixture, as greater quantities have the potential to cause problems with engine functionality and durability. Blends such as B2 and B5, which consist of 2 and 5% biodiesel, respectively, are typically compatible with the majority of contemporary diesel engines without requiring any alterations. These low mixes provide a seamless transition to renewable fuels, reducing any negative effects on engine performance. Nevertheless, stronger blends such as B20, which contain 20% biodiesel, necessitate a more careful approach. Although they provide substantial environmental advantages, they may require engine tweaks or upgrades to achieve optimal performance. Engine components such as fuel injectors and seals may experience increased wear and damage when exposed to higher amounts of biodiesel. In addition, several older engine models may not be suitable for use with B20 blends, necessitating a thorough evaluation and possible modifications.

4.4 Impact of biodiesel on emissions and air quality

Biodiesel blends provide a notable benefit compared to traditional diesel in terms of mitigating detrimental emissions and enhancing air quality. Substituting a fraction of fossil fuel with biodiesel leads to a significant decrease in greenhouse gas emissions, specifically carbon dioxide (CO_2), which is a primary cause of climate change. The renewable nature of biodiesel enables a carbon-neutral lifecycle, so further reducing the environmental impact of transportation.

4.5 Applications in transportation, agriculture, and other sectors

Biodiesel's adaptability extends beyond the transportation sector, as it may be applied in numerous industries, thereby contributing to a cleaner and more sustainable future. Biodiesel mixes may be easily incorporated into current diesel engines, allowing them to fuel a wide range of vehicles, including passenger cars, heavy-duty trucks, and busses. These mixtures greatly decrease the release of greenhouse gases and particulate matter, leading to better air quality and supporting more environmentally friendly transportation. Furthermore, the biodegradability of biodiesel provides a safer option in the event of spills, hence reducing environmental harm. Biodiesel is an excellent fuel for farm equipment in agriculture, as it effectively reduces emissions and decreases dependence on fossil fuels. This contributes to enhancing air quality in rural regions and diminishing the carbon footprint of agricultural activities. Biodiesel can serve as a bio-pesticide, efficiently managing specific pests with reduced environmental effects compared to other pesticides. In addition to these main areas, biodiesel is used in several industries. The utilization of this technology in heating systems and power generation provides a viable substitute for fossil fuels, resulting in a decrease in emissions and the advancement of energy self-sufficiency. Biodiesel can serve as a lubricant in diverse industrial applications, demonstrating its wide-ranging potential. As ongoing research and development progresses, biodiesel is revealing new possibilities for its utilization, showcasing its capacity to contribute to a future that is both more sustainable and environmentally cleaner. Biodiesel provides a flexible and eco-friendly solution for various sectors, including transportation, agriculture, and industry, contributing to a greener and more sustainable society [28].

5. Economic and environmental aspects of biodiesel

Biodiesel offers a persuasive argument for a sustainable future, with its combination of economic and environmental advantages. However, it also presents a set of obstacles that need to be carefully examined. Regarding ecology, biodiesel stands out as a highly favorable option. The renewable nature of this substance, which is obtained from vegetable oils or animal fats, greatly decreases the dependence on fossil fuels, leading to a large decrease in greenhouse gas emissions and helping to mitigate climate change. In addition, biodiesel combustion is more environmentally friendly as it emits fewer detrimental pollutants such as particulate matter and sulphur dioxide, hence enhancing air quality and public health. The biodegradability of the product provides an additional level of environmental protection, reducing the potential harm in the event of spills.

Nevertheless, the economic terrain of biodiesel is quite intricate. Although the positive impact on the environment is unquestionable, the expense associated with production continues to be a major obstacle. Volatility in feedstock prices, such as vegetable oils, can have a substantial impact on the expenses associated with biodiesel manufacturing. Furthermore, the establishment and maintenance of the necessary infrastructure for the production and distribution of biodiesel necessitates financial investment, which may have an immediate effect on its economic viability.

5.1 Cost analysis of biodiesel production

The cost of producing biodiesel is a critical determinant in its widespread acceptance, as it affects its competitiveness compared to traditional diesel fuel. An exhaustive cost study must take into account multiple elements, such as feedstock expenses, processing costs, and possible subsidies or incentives. Although biodiesel has substantial environmental advantages, the present cost of producing it remains a considerable obstacle.

According to data from the US Department of Energy, the average expense for producing biodiesel in 2022 was roughly $4.50 per gallon, which is considerably greater than the cost of regular diesel at around $3.50 per gallon. The main reason for this disparity in cost is mostly due to the elevated expenses associated with feedstocks, such as soybean oil and recycled cooking oil, which constitutes a significant proportion of the overall production cost.

5.2 Life cycle assessment of biodiesel

Life cycle assessment (LCA) offers a thorough examination of the environmental effects of biodiesel production and utilization across all stages, starting with the extraction of raw materials to the ultimate disposal. In 2019, the US Department of Energy conducted a thorough life cycle assessment (LCA) research which found that biodiesel made from soybean oil led to a significant 78% decrease in greenhouse gas emissions when compared to regular diesel fuel [35]. The considerable decrease is ascribed to the renewable characteristic of soybean oil and the capacity of soybeans to sequester carbon throughout their growth. Additional investigation revealed that the production of biodiesel can result in a decrease in the consumption of fossil fuels, thus contributing to achieving energy independence and alleviating the impacts of climate change. Nevertheless, the study also emphasized the possible environmental consequences linked to alterations in land use and the usage of fertilizers in soybean farming. The results of the life cycle assessment (LCA) might vary considerably based on factors such as the type of feedstock utilized, the production methods employed, and the unique geographic region. Biodiesel manufactured from waste-based feedstocks, such as recycled cooking oil, generally has lesser environmental impacts compared to biodiesel made from virgin oils [36, 37]. These findings highlight the need to improve biodiesel production procedures and select the most suitable feedstock to reduce environmental consequences. Moreover, LCA studies can provide guidance for policy makers in determining the appropriate incentives for sustainable production methods and the promotion of biodiesel blends. This can help in decreasing greenhouse gas emissions and advancing a cleaner transportation sector.

6. Conclusion

Biodiesel is an ecologically viable and environmentally advantageous substitute for conventional diesel fuel, which is increasingly being acknowledged for its positive environmental attributes and long-term viability. Biodiesel, which emerged in the late nineteenth century, has enhanced lubricating capabilities, decreased sulfur content, and reduced emissions. It is derived from sustainable sources, hence reducing reliance on fossil fuel reserves and decreasing greenhouse gas emissions. Nevertheless, the need to address land use changes and the increasing demand for biodiesel feedstock necessitate a meticulous focus on implementing sustainable production methods. Biodiesel production provides benefits such as the diversification of energy sources, enhanced energy security, and reduced dependence on imported oil. Nevertheless, there are still obstacles to overcome when it comes to expanding the cultivation of algae and maximizing the lipid content for the purpose of producing biofuels on a large scale. Optimal feedstock selection is essential for reducing land use change, water consumption, greenhouse gas emissions, biodiversity preservation, and social consequences. Transesterification is an essential step in the manufacturing of biodiesel, in which triglycerides are transformed into fatty acid methyl esters (FAMEs) and glycerol. The availability, quality, and conversion efficiency of biodiesel production have been enhanced due to advancements in feedstock development and processing technologies. Biodiesel production methods encompass a range of procedures and equipment used to transform feedstock oils and fats into biodiesel fuel. The future of the biodiesel business will be significantly influenced by improvements in equipment design and process optimization. Biodiesel exhibits superior lubricity characteristics, possesses a higher viscosity compared to petroleum diesel, and has marginally lower energy content than petroleum diesel.

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Chapter 3

The Essential Properties of Oils for Biodiesel Production

Sunday Ifeanyichukwu Umeh and Peter Anadebe Okonkwo

Abstract

The quest for production of high-quality biodiesel with improved combustion properties at low cost, and the commercialization of biodiesel, has remained a relevant topic in today's global energy market due to the need to achieve extensive substitution of fossil diesel with biodiesel fuel. This chapter examined the essential properties of oils for optimal biodiesel production and provided a comprehensive guideline for identification of suitable biodiesel oil feed-stocks, selection of appropriate processing parameters as well as methods for the optimized production of high-quality biodiesel at minimal cost. It enumerated the various essential properties of oil feed-stocks for biodiesel production, known as the physicochemical properties of biodiesel feedstock oils. The properties include viscosity, specific gravity, flash point, kinematic viscosity, free fatty acid, saponification value, acid value, moisture content, calorific value, cetane number, cloud point, pour point, oxidation stability, iodine value, peroxide value, and refractive index. The determination of the oils' characteristics, and comparison with recommended ASTM D6751 values, prior to the conversion of the oils to biodiesel is essential for selecting the best pretreatment and post-treatment methods to be deployed in the biodiesel production process. The oils' properties, which are closely related to the biodiesel performance characteristics, determine the quality of biodiesel, its yield, the produced biodiesel performance in engines, and aid in determining how to handle the bio-oil conversion process to obtain biodiesel with enhanced properties. In writing this chapter, a comprehensive review of research publications, conference papers on biodiesel production and other related articles, was undertaken, and the findings presented.

Keywords: biodiesel feedstock, oil, alternative fuel, physicochemical properties, triglycerides, saponification value, transesterification, free fatty acid

1. Introduction

Biodiesel, as a renewable energy resource, has grown to become an acceptable global alternative to hydrocarbon diesel fuel, owing to its less harmful impacts on the environment in comparison to petroleum diesel [1]. The physical properties of these fatty acid esters, called biodiesel, have been found to be very close to those of fossil diesel fuel [2, 3]. Biodiesel is the diesel fuel produced from natural oils and fats, obtained from plants and animals. It is a mixture of mono-akyl esters of long-chain fatty acids obtained from the upgrading conversion of vegetable oils or animal fats [4–6]. This diesel was invented in order to overcome the limitations associated with the direct use of vegetable oils and fats in engines, such as very high viscosity [4], about 10 times greater than fossil diesel [7]; lower volatility; poor cold-flow properties; and polyunsaturated behavior, in comparison to conventional diesel fuel, which limited its utilization in diesel engines or as a diesel fuel alternative [8, 9]. Out of the many methods that are used for the conversion of oils to biodiesel, such as dilution, micro-emulsification, pyrolysis (thermal cracking), supercritical methanol treatment, hydro-processing, ultrasonic treatment, and transesterification [10], the most efficient and also the most commonly used method is the transesterification method [1], though the hydro-processing method is reported to yield biodistillate known as green diesel, obtained from the same straight-chain vegetable oils as reactants, which releases lesser emissions than biodiesel produced through transesterification [8, 10–14]. Biodiesel is one of the end products of the conversion of triglycerides of vegetable oils, some microalgae lipids, and animal fats into methyl or ethyl esters by the catalyzed process of transesterification. Transesterification is the catalyzed process of exchanging the organic functional group R^{II} of an ester with the organic group R^{I} of an alcohol [15]. This mixture of the esters of long-chain fatty acids in the oils and fats has properties that are as varied as the feedstock from which they are produced, with some desirable and others undesirable. Biodiesel could be produced from any plant or animal product that is capable of releasing oil or fat after treatment processes. This implies that many varieties of raw feedstock materials are available, but not all of them possess suitable requirements for oil production for conversion to biodiesel. Lois et al. [16] listed the criteria for selecting suitable feedstock materials for oil production to include availability, cost, yield, and quality. Globally, various technical optimization methods are deployed to improve these listed criteria for feedstock qualification for biodiesel production. It is reported in the literature that there are up to 320 different kinds of plants whose seeds contain up to 15% fats, which can be used for biodiesel production [16]. Low oil yield is an indication that a feedstock may not be a good source of abundant oil [17]. Biodiesel yield and performance characteristics have been found to be highly dependent on the type of oil feedstock from which the biodiesel is produced. Hence, the first critical stages in the biodiesel production process are the selection, sourcing, and preparation of the reactants in the right proportions [10]. Igbax et al. [10] and Suraj et al. [7] listed the factors that affect the biodiesel yield during the transesterification process to include the reaction temperature, alcohol type, molar ratio of alcohol to vegetable oil, catalyst type, concentration of catalyst, mixing intensity of the process, and free fatty acid (FFA) content of the vegetable oil. Today, the physicochemical properties of biodiesel have been standardized so that they can give optimal performance on diesel engines, either for automobile applications or for power generation purposes. The physicochemical properties of any biodiesel have been found to be dependent on the physicochemical properties of the oil from which it is produced and hence often form the basis, for the characterization of the biodiesel produced therefrom. Okonkwo and Omenihu [2] reported that the chemical properties that mostly determine the behavior of biodiesel's performance are the degree of "branching" in the chain, the length of the biodiesel molecule, the degree of saturation of the molecule, as well as the cold-starting properties of the diesel. Additionally, the chemical structure of the alcohol, the nature, and the concentration of the catalyst employed have been found to affect the properties of the biodiesel produced from oils. The main feedstocks used in the production of biodiesel are vegetable oils, algae, animal fats, and waste cooking oils (WCO) [18–20]. Ajala et al. [3] reported that more than 70% of the biodiesel production costs depend on the price of feedstock and suggested that the use of low-cost raw materials like WCO could bring down the cost to about 50% in comparison with fresh palm oil in Thailand. However, the use of WCO is limited by its high free fatty acid (FFA) and water content, to the effect that the FFA content in WCO often reacts with the base catalyst to form soap via saponification reaction, which consumes the catalyst, thereby resulting in a lower yield of biodiesel, while the water content often participates in the hydrolysis of the biodiesel to release FFA and alcohol, producing the same negative effect [21, 22]. Another promising way of bringing down the cost of biodiesel production is through the application of a mixture of two or more oils as feedstock, either non-edible or edible oil (hybrid oil), for biodiesel synthesis [23]. It has also been reported that the choice of catalyst selected for the biodiesel conversion process could be another cost-reduction strategy that would enhance the commercialization of biodiesel [14, 23]. The types of catalysts employed for the production of biodiesels are homogeneous and heterogeneous catalysts [18, 24, 25]. Brahma et al. [23] and Galadima et al. [24] reported that heterogeneous catalysts are more beneficial for transesterification in terms of reusability, recovery, product purity, and production cost. Canola oil has been reported to be one of the most effective and efficient sources of oil for biodiesel production with excellent cold-flow properties [26]. Blending biodiesel with other fuels has been used over the years as one of the successful strategies for significantly improving its properties, which aids in increasing the global market share of biodiesel use as fuel [27]. Sakthivel et al. [28] have presented a list of some feedstock used for biodiesel production.

This chapter discusses the relevant properties of oils required for optimal biodiesel yield, at a reduced cost of conversion to biodiesel, and with improved performance in diesel engines. Over the years, research has revealed that some oils have many properties that progress the biodiesel production process reaction stages and enhance biodiesel yield as well as the performance of the diesel fuel in compression ignition engines. These properties usually lend the feedstock oils as a good, affordable, and viable candidate for quality biodiesel production. The feedstock oil's properties include viscosity, specific gravity, flash point, kinematic viscosity, free fatty acid, saponification value, acid value, moisture content, calorific value, cetane number, cloud point, pour point, oxidation stability, iodine value, peroxide value, and refractive index.

1.1 Viscosity

The viscous property of fluids is one of the most important properties of oils, which also determines the quality of the biodiesel produced from the oils. The kinematic viscosity of any liquid is the resistance of a liquid to flow in the presence of gravity, and it is inversely proportional to the flow velocity [6, 10, 26, 29]. The viscosity of any engine fuel plays a dominant role in the fuel spray, mixture formation, and combustion process [19]. The high viscosity of vegetable oils and animal fats is the main reason why they are not used directly in diesel engines, as they tend to create problems such as engine deposits, piston ring sticking, injector coking, and thickening of the lubricating oil [8]. Hence, the major goal of the transesterification process of oil conversion to biodiesel is basically to reduce the viscosity of the oils [19, 26, 30]. The key process in the biodiesel production lies in the transesterification of the raw materials; vegetable oils, algae lipids and fats, using a short chain alcohol [21]. The viscosity of oils and even biodiesel often determines the applicability of any fuel in diesel engines or otherwise, as it creates one of the key challenges to efficient fuel flow, fuel spray, fuel atomization, fuel-air mixing, early injection, increased maximum pressure and temperature in the combustion chamber, continuous combustion, and steady power production in engines [19, 26, 30]. Moreover, the mean diameter of the fuel droplets from the injector and their penetration increases with increasing fuel viscosity [6, 19]. Viscosity is important because the molecular transport of any oil controls the dynamic behavior of the fluid, its movement, dilution, reaction, and transformation [29]. The free fatty acid content of any oil plays a significant role in the thermo-physical properties of oil, of which viscosity is one of them [2, 29]. Awogbemi et al. [29] observed that the viscosity of oil is usually indicated by the titration value and the mass spectra analysis of the oil. The viscosity of a fluid has been found to depend on temperature, with the viscosity of oils decreasing with increasing temperature [31], and this tends to progress the production of biodiesel. It is reported in Ref. [10] that fluids that undergo rapid deformation on the application of heat usually react faster when mixed with alcohol. The viscosity of the feedstock oil for biodiesel can indicate the ease or difficulty of its conversion to biodiesel as well as the biodiesel quality and production efficiency [20, 32]. The viscosity of the feedstock oil is an important determinant of the biodiesel flow characteristics. The range of viscosity of oils for efficient and optimal biodiesel performance is 3.74–5.75 centistokes [10]. High-viscosity oil feedstock usually yields high-viscosity biodiesel, while low-viscosity oil will yield biodiesel with low viscosity. It has been observed that the conversion of oil to biodiesel leads to a reduction in the viscosity of the biodiesel produced. The kinematic viscosity of the oils usually drops after the transesterification process. It is reported in Ref. [33] that the kinematic viscosity of coconut oil dropped from 27 to 2.4 mm^2/s after transesterification. Furthermore, the viscosity of canola oil was reported in Ref. [34] to be 70 mm^2/s, at 21°C, but its ethyl ester biodiesel measured 5.03 mm^2/s at 40°C. This is, however, still within the ASTM standard range of 1.9–6.0 mm^2/s at 40°C. When the viscosity of the oil feedstock is too high, the conversion of the oil to biodiesel becomes more demanding and expensive in terms of resources: catalyst, reagents, energy, and time. A low-viscosity oil feedstock will yield biodiesel with even lower viscosity and hence will require further expensive treatments (blending and addition of additives) to bring it within the recommended ASTM D6751 standard. Otherwise, in both cases, such fuel could only be used for blending. Biodiesel is reported to possess many technical advantages over fossil diesel, which include low toxicity, derivability from renewable and domestic feedstock, superior flash point, biodegradability, and negligible sulfur content [35, 36], which translates to longer life of the automobile catalytic converters, while the viscosity of the biodiesel offers adequate lubrication to the engine, thereby increasing the life of the engine [10]. However, neither very high nor very low viscosity is considered desirable for a diesel engine, as excessively high viscous biodiesel has been reported to have some adverse effects on the automobile engine. The commonly reported effects include pump damage and filter clogging, poor atomization and combustion, difficulty in fuel evaporation, increased emissions, and sedimentation in the fuel tank [6, 19, 37, 38]. The reduction of the kinematic viscosity of biodiesel can be achieved in many ways, including the preheating method, blending with low-viscosity fuel, and the application of additives [6]. On the other hand, low-viscosity biodiesels have been credited with excessive injection pump wear and power loss due to injector or pump leakage, increased erosion, and leaks in the fuel system [20, 26, 32, 39, 40]. It is reported in Ref. [10] that the range of viscosity of oils for efficient biodiesel performance is 3.74–5.75 cSt (centistokes). The viscosity of any liquid is usually determined with a viscometer [41], and is normally rated in Centipoise (cP), which is equivalent to 1 × 10^{-3} Ns/m^2, which is the SI units for viscosity. The viscosity of any fluid, including oils and biodiesels, could also be determined by a titration process. The viscosity of biodiesel is determined based on the ASTM D6751 international standard. The kinematic viscosity of biodiesel must be determined at 313K as required by the ASTM D445 standard, and the measurement must take at least 200s. However, it could take a longer time depending on the oil feedstock and the size of the viscometer used. Though the method described in ASTM D445 yields highly accurate results, it is reported in Ref. [26] to be slow and hence cannot easily be adapted to online measurements. Detailed information on the method of determination of viscosity of oil can be found in Ref. [41]. The ASTM D6751 standard has recommended that the kinematic viscosity of biodiesel for CI engines should be in the range of 1.9–6.0 mm^2/s, while for the EN14214 standard, the allowable kinematic viscosity values are between 3.5 and 5.0 mm^2/s [4]. Therefore, it goes without saying that feedstock oil whose viscosity is greatly below or above the specified range will not serve as economically viable oil for biodiesel production. Biodiesel is reported to have a higher viscosity than fossil diesel because it has a high fatty acid composition [33, 34, 42]. The kinematic viscosity of biodiesel is reported in Ref. [43] to be 2–4 times higher than that of conventional diesel or fossil diesel fuel at room temperature, and this happens to be one of the biggest disadvantages of biodiesel in contrast to the conventional petroleum diesel fuel. The viscosity of any fuel is related to the chemical structure of the fuel [19]. The high viscosity of biodiesel is due to its high molecular mass and large chemical structure compared to that of diesel fuel. Viscosity increases with an increase in the chain length and decreases with an increase in the number of double bonds (degree of unsaturation). Canakci and Sanli [19] reported that the viscosity and heat content of feedstocks and biodiesel fuels tend to increase together. An advantage of the higher viscosity of biodiesel over diesel fuel is that biodiesel has a high lubricity property, which makes it a good additive for enhancing the lubricity of conventional diesel fuel, even on a small scale level [19, 44]. The quality and type of fatty acid content in a biodiesel usually determine the viscosity of the fuel. The fatty acid composition of biodiesel determines its degree of saturation, with a higher fatty acid composition giving rise to a higher degree of saturation and vice versa. Canola oil is reported to be one of the most effective and efficient sources of oil for biodiesel production [1], with excellent cold-flow properties, owing to its low saturated fat content, and it is reported to meet the 50% greenhouse gas reduction requirement of the U.S. Environmental Protection Agency (EPA) as a raw material or feedstock for biodiesel production under the Renewable Fuel Standard as well as the feedstock requirements in Canada and the European Union [45]. The major saturated fatty acids found in waste cooking ethyl ester are palmitic and stearic acids [34, 46]. A report of the engine performance evaluation conducted by Tuccar et al. [47] on a four-stroke, four-cylinder diesel engine revealed that carbon monoxide (CO) emission was reduced with the utilization of diesel fuels that have higher viscosity and density, while the emissions of Carbon dioxide (CO_2) and the oxides of nitrogen (NO_x) increased with decreasing viscosity and density.

1.2 Density/specific gravity

Density is a property of matter, and it is defined as the mass of a material per unit volume of the material. On the other hand, the specific gravity of a material is the ratio of the material's density to that of water at 4°C. Hence the density of any fluid is directly proportional to its specific gravity. Density, or better still, specific gravity, is another important property of oil that helps to determine the quality of the biodiesel produced from the given oil. Density is generally related to the energy content of a fuel [48]. On a volumetric basis, the higher the density of any fuel, the greater the potential energy content of the fuel [49]. There is a direct linear relationship between the feedstock oil densities and the density of the biodiesel produced from the given oil. In other words, the higher the density of the feedstock oil, the higher the density of the biodiesel produced from it. It is reported in Ref. [34, 50] that density is also a function of temperature and that it decreases linearly with temperature. As is the case with viscosity, the conversion of oils to biodiesel usually leads to a reduction in the density of the biodiesel product. The density of waste cooking oil, which was originally 90 g/cm^3 at 21°C, measured 87 g/cm^3 at 15°C after conversion to biodiesel [34]. Feedstock oil with a very high density will require a higher processing cost than oil with an average density value. This processing cost is usually incurred by either raising the temperature of the oil, using an expensive and high concentration of catalyst, using a high molar ratio of reactants, or by multiple oil treatments; otherwise, the biodiesel yield will be poor [19, 34, 43]. The higher the reaction temperature used for the conversion process, the lower the density of the biodiesel produced. An increase in temperature would cause the molecules of the oil to move faster and create conditions for more collision, and the more the collision, the faster and more the conversion process will yield [8, 10, 18, 43, 44, 51–53]. Untreated oil feedstock with very high density will ultimately yield biodiesel whose specific gravity will most likely be outside the acceptable limits of the ASTM D6751 standard. The ASTM D6751 recommends that the density for biodiesel acceptable for good performance of diesel engines should be between 860 and 900 kg/m^3, while the specific gravity should be 0.88 maximum. Ismail and Ali [54] reported that the density of any biodiesel depends on the raw materials from which it is produced and the biodiesel ester profile. Ginting et al. [18] reported that poor purification of biodiesel at the purification stage could cause the density of the produced biodiesel, even from the same feedstock, to vary. All biodiesels, regardless of the feedstock of production, vegetable oils, or fats, are denser and less compressible than conventional diesel fuel. Density is closely related to viscosity; the higher the viscosity of any fuel, the higher the density value [18, 25]. And like viscosity, density, and compressibility impact critically on the engine fuel injection system. The injected fuel quantity, injection timing, and injection spray pattern are directly influenced by these parameters [19]. High-density fuel will release fuel droplets with high diameters, with the attendant big inertia, leading to higher penetrations in the combustion chamber [4]. However, a fuel with lower density and viscosity, if injected in the same engine, will offer better and improved atomization and air-fuel mixture formation [19, 47, 51, 55]. Density prediction is of high importance for a correct selection and formulation of an adequate blend of feedstock materials that will optimize the cost of biodiesel production and, at the same time, allow the produced fuel to meet the required quality standard [19, 33, 51]. High fuel density has adverse effects on diesel engines, fuel systems, and exhaust emissions. If a biodiesel fuel has a very high density compared to another, the implication is that more mass will enter the combustion chamber for the same cylinder volume [19, 51, 56]. And since diesel injectors, which supply fuel into the combustion chamber, regulate the quantity of fuel by volume, much more fuel will enter into the cylinder within any given time, leading to increased emissions of particulate matter (PM) and oxides of nitrogen (NO_x) [19, 47, 54]. Biodiesels usually have a higher density than fossil diesel (839 kg/m^3), and for this reason, biodiesels are termed "chemically advanced fuels" in terms of injection timing. The implication of this is that for the same engine, biodiesel will take a shorter time to travel from the injection pump to the injector when compared with conventional diesel fuel. This high-density effect of biodiesel on injection timing is reported in Ref. [19, 33, 56] to be advantageous to biodiesel, as it usually compensates for the lower calorific or heating value of biodiesel. The chain length and degree of saturation also impact the density of any biodiesel. As biodiesels produced from feedstocks that have more saturated fatty acids, such as fats or greases, have higher densities than those of biodiesels from vegetable oils [19].

1.3 Flash point

This is an important safety indicator for any fuel. The flash point of any liquid is the lowest temperature at which the liquid will form vapor in the air surrounding its surface, which, upon exposure to an open flame, will briefly ignite or catch fire. The flash point serves as a general indicator of the flammability or combustibility of a fuel. It is generally used to assess the hazard level associated with a flammable liquid in order to determine its fire and explosion risk as well as the required handling care. The lower the flash point of a fuel, the more flammable the fuel is and the greater the fire risk of the fuel. The factors that affect the flash point of oil include vapor pressure, molecular structure, composition range, lower flammability limit, boiling point, moisture content, heating speed, and enthalpy of vaporization. Flash point is a safety indicator for the storage, transportation, and use of flammable liquids, especially fuels, as well as a volatility indicator for the flammability of liquids. The higher the flash point of any oil or fuel, the lower the risk of fire hazard during storage when exposed to a high-temperature source of heat. On the other hand, liquids (oils or fuels) with low flash points and high volatility are easily ignited and pose poor safety conditions. The flash point of an oil product indicates its flammability, content of volatile compounds, degree of gasification, and safety [57]. The hazard level of oil products and fuels can also be classified on the basis of their flash point; thus, oils or fuels with a flash point below 61°C are regarded as inflammable, while those with a flash point above are considered as flammable. The two methods of determining the flashpoint of oil products are the closed-cup method and the open-cup method. The flash point of fuels and light oil products is determined using the closed-cup method, while the open-cup method is used to determine the flash point of heavy oil products [57]. Though the flash point of oils usually decreases after conversion to biodiesel, it is still higher than those of diesel fuel regardless of whether the biodiesel is from high-quality vegetable oils or from low-cost feedstocks [19]. A comparison of the flash points of low-cost feedstocks shows that the flash points of biodiesels from low-cost feedstocks are higher than those from vegetable oils since they contain more saturated fatty acid. The Pensky-Martin or Gray's apparatus can be used to determine experimentally the flash point of a liquid fuel [49]. Oil feedstock with a high flash point indicates that it has low volatile material contaminants and will yield more biodiesel than the one with a low flash point. In addition, oil feedstock with a high flash point will also yield a biodiesel that will be safer to handle and transport. Biodiesels are safer in transportation than diesel fuel because they usually have higher flash points than diesel fuels [8]. The flash point of a fuel has a correlation with its volatility, and it is an important fuel property for engine starting and warming, and the combined effect of high viscosity and low volatility of any fuel will cause bad cold engine start-up, misfire, and ignition delay [19]. The ASTM D6751 recommended that the minimum flash point of biodiesel for compression ignition engines should be 130°C [28] and 101°C based on the EN14214, EN 2012 standard [58]. Bazooyar et al. [8]

recommended that biodiesels should be tested for assessment of safety risks and environmental pollution in order to serve as assurance from suppliers and producers and to sustain the confidence of users. A detailed method for the determination of the flash point of liquids, especially biodiesel, is presented in Ref. [59].

1.4 Free fatty acid

The free fatty acid (FFA) is an important property that is used to assess the quality and commercial value of oils and fats. It has been found to be the major cause of instability in vegetable oils [14]. The free fatty acids (FFAs) in fats or oils are usually produced by the hydrolysis of the fats and oils, with the amount of FFAs produced depending on time, temperature, and moisture content. It is reported in Ref. [60] that FFAs are less stable than neutral oils; they are more prone to oxidation and turning rancid when exposed to various environments such as storage, processing, heating, or frying. The low FFA content of any oil is indicative of low enzymatic hydrolysis [17], which presents a better shelf life for the oil [61]. However, high free fatty acids (FFAs) content in oils usually greatly reduces the effectiveness and efficiency of the alkali-catalyzed transesterification process, used most commonly for the conversion of oils to biodiesel, and decreases the production yield [60, 62]. In order to improve the biodiesel yield from fats and oils with high FFA values, such oils are usually converted to biodiesels via a two-step reaction process, namely, acid-catalyzed esterification pretreatment and alkali-catalyzed transesterification. It is reported in Ref. [3, 63] that the first step, which involves an acid-catalyzed esterification reaction, is a necessary pretreatment usually employed in order to decrease or reduce the FFA content of any fats or oils and make them suitable for the transesterification process to biodiesel. The acid esterification process usually increases the cost of the biodiesel production process. Ajala et al. [3] recommended that oils with FFA content of more than 1% should be subjected to the acid esterification process in order to obtain optimal yield of biodiesel from the oil using the transesterification conversion process. Moreover, high free fatty acid contents of oils can result in soap formation in the presence of potassium hydroxide and water during the transesterification reaction of the oil [62, 64], which makes washing the finished product more difficult [65]. The FFA content of any oils or fats is usually determined based on the standard titration method, in which oils or fats are dissolved in hot neutralized ethanol or ethanol/diethyl ether using phenolphthalein as an endpoint indicator. The fatty acid contents of any biodiesel are a major indicator of its properties [34]. Free fatty acids in biodiesel could be a result of incomplete transesterification reactions during the oil's conversion process. Banga and Varshney [14] reported that FFAs may either degrade or cause corrosion and thermal instability or could even undergo oxidation and break down into aldehydes, ketones, epoxides, and even alcohols. Report research by Chhetri et al. [34] revealed that approximately 60% of fatty acids found in waste cooking oil biodiesel were monounsaturated (C18:1), while polyunsaturated fatty acids amounted to approximately 26% (C18:2, C18:3), with saturated fatty acids accounting for only 8%. Okonkwo and Omenihu [2] reported that canola oil, with its high proportion of long unsaturated fats (lots of oleic acids), is, for now, the most preferred oil for quality biodiesel fuel production and that out of the assorted types of fatty acids found in vegetable oils, the oleic acid is the best, the linoleic acid is less undesirable, and the linolenic acid is the most undesirable [66]. The CDR FoodLab [67] observed that the FFA could be used as a measure of the level of degradation of fats and has been used more recently as a parameter for detecting the conditions of vegetable oils used as biofuels for the production of green power.

The various types of fatty acids found in Waste Cooking Oils (WCO) as revealed by a Gas Chromatographic Analysis were reported by Chhetri et al. [34]. It is reported in Ref. [68] that the purity of biodiesel decreased from 97.2% to 95.0% when the FFA content of any oil is increased from 0% to 4%, and that the maximum FFA content in good quality feedstock for biodiesel production should be less than 1.0% [69]. It has been reported that the biodiesel yield from oils decreases with increasing values of FFA with the application of single-stage alkali transesterification of oils. Suraj et al. [7] reported that alkali transesterification of vegetable oils having less than 2% FFAs produced a biodiesel yield of 95%, but the yield decreased below 80% for oils with FFAs above 3.6%, while the process failed for oils having FFAs above 4.2%. The vegetable oils of corn, neem, and rubber seeds were found to have FFA values of 0.28, 12.1, and 47.1%, respectively [7]. Banga and Varshney [14] reported that heterogeneous catalysts are more efficient in the transesterification of high FFA oils than homogeneous catalysts. Many qualitative and quantitative methods have been successfully deployed for the determination of the various functional groups present in oils and fats. Anang et al. [17] reported the use of Fourier Transform Infrared (FTIR) Analysis for the determination of the various functional groups in feedstock oils, while Ginting et al. [18] and Omeje et al. [70] successfully deployed the Gas Chromatography-mass spectrometry analysis for the identification and quantification of the fatty acids in substances.

1.5 Saponification value

The saponification value (SV), which is also known as the saponification number, indicates the quantity of potassium hydroxide (KOH) needed to saponify (or convert to soap) 1 g of oil. The saponification value of an oil sample is a measure of the chain length (or average molecular weight) of all the fatty acids in the oil. Soares and Rocha [71] reported that the saponification value, together with the iodine value of oil, could be used to estimate the number of double bonds in a neat fatty compound. The saponification value of oil can be used to determine the number of acids (esters and free acids) in any fat or oil. The SV usually provides a direct measure of the average molecular weight of any oil. Mihaela et al. [72] observed that the higher the saponification value, the lower the fatty acids' average length and the lighter the mean molecular weight of the triglycerides. A small saponification value or number indicates the presence of long-chain fatty acids on the glycerol backbone in an oil sample, while a high saponification value indicates triacylglycerols with shorter fatty acyl chains [54, 72]. Fats or oils from coconut and palm oil, with high saponification values, do not yield much biodiesels; rather they are more suitable for soap making [17, 72]. Peter and Agwupuye [65] observed that saponification values greater than 200 mg KOH/g indicate the presence of fatty acids of low or fairly low molecular weight, while saponification values of less than 190 mg KOH/g indicate higher molecular weight fatty acids. It is also reported in Ref. [72] that the common oils/fats from vegetable or animal sources including soybean, sunflower, rapeseed, pork lard, chicken fats, and beef tallow, that contain mainly long-chain fatty acids of between C16 and C18, have saponification value ranges of 168–196 mg KOH/g oil, but other vegetable oils like palm and coconut oils with large amounts of lauric C12:0 and myristic C14:0 acids have saponification values that are remarkably higher, ranging from 235 to 260 mg KOH/g oil. It therefore follows from the foregoing that fats or oils with very high SV may not be economically viable as feedstock for the production of biodiesel. SV is usually determined by the titration method; however, other methods like the Fourier transform infrared spectroscopy (FTIR) coupled with multivariate analysis [73] and the fast, as well as non-destructive, 1H-NmR spectroscopy applied by Mihaela Ivanova et al. [72] for the analysis of edible oil, have equally yielded commendable results. SV is conventionally determined by saponification of a known amount of fat or oil with an excess quantity of KOH solution, followed by back titration of the excess base with an acid solution in the presence of phenolphthalein as an indicator. The amount of the base needed for saponification of fatty acyl chains is then indirectly determined [72]. Though Mihaela Ivanova et al. [72] provided a detailed method for the determination of the SV of oils, the ASTM D5558-95 standard has provided the guidelines for the measurement of the saponification values of oils for the range of 0–370 mg KOH/g. Chicken fat methyl ester (or biodiesel) has a saponification value of 251.23 mg KOH/g of the oil [72], whereas waste frying oil biodiesel has a value ranging from 191.03 to 195.91 mg KOH/g [54, 72].

1.6 Acid value

This is also known as acid number or total acid number (TAN) and is used as a measure of the amount of mineral acids and free fatty acids in an oil sample. Acid number is a measure of auto-oxidation, storage stability, or material contamination. It represents the total amount in milligrams of KOH required to completely neutralize 1 g of the oil or biodiesel sample. Anang et al. [17] reported that the acid value of a good oil for biodiesel production should be very low (<0.1). Oils with an acid value of less than 0.1 will result in low oil oxidation, with no possibility of gum and sludge formation [61]. A high acid value indicates that the oil is unstable and will readily react with environmental elements [74], leading to gum and sludge formation as well as corrosion [17]. Titration is usually applied for the determination of the total acid number of oils. Oklahoma State University Extension [75] reported that the maximum acid value for biodiesel should be 0.8 mg KOH/g. The ASTM D6751 standard and the Europe EN14214 for acid value (AV) of pure biodiesel is 0.5 mg KOH/g, and the test conditions for the determination of the acid value of biodiesel are described in the ASTM D664 standard and for Europe EN14104. The higher the acid value of a fuel the more unstable the fuel, will be [34, 76]. Chhetri et al. [34] reported that high acid values of biodiesels are usually the result of unrefined or poorly refined oil feedstock due to poor process control, such as ethanol carryover. Furthermore, fuels with high acid numbers have strong solvent tendency effects [65] and usually attack rubber seals and hoses, causing degradation of such rubber parts in engines and leading to filter clogging [34]. The acid values of some ethyl esters or biodiesels of some oils, as reported by Lang et al. [77], are 0.884, 0.869, 0.876, and 0.873 mg KOH/g for the ethyl esters of linseed oil, canola oil, sunflower oil, and rapeseed oil, respectively, while Chhetri et al. [34] reported 0.29 mg KOH/g for Waste cooking oil (WCO) biodiesel. The acid value of biodiesels can be improved by tight control of the transesterification, cleaning, and drying processes during the biodiesel conversion process.

1.7 Moisture content

This is another important parameter that affects both the yield and the quality of biodiesel obtained from any oil. The high moisture content of oils is usually due to poor preparation of the oils. Feedstock oils that contain high moisture content are always problematic, because the base catalyst often used in the transesterification process, in the presence of the high water content, does participate in the reaction leading to hydrolysis of the biodiesel to produce additional Free Fatty Acids (FFAs) and methanol [21, 62]. Both hydrolysis and saponification reactions have been found to cause low biodiesel yield and catalyst contamination and consumption [19, 62, 64, 78], which ultimately increases the cost of biodiesel production and, in turn, causes the deterioration of the fuel characteristics of the biodiesel [79]. As a precautionary measure aimed at preventing hydrolysis, saponification, and the reduction of catalyst effectiveness, the oil for the production of biodiesel is usually preheated to a temperature of between 60°C and 90°C in order to minimize the water content of the oil [14]. The FFA and moisture contents in oil feedstocks for biodiesel production must be carefully controlled to prevent soap formation [14]. The maximum amount of allowable water content in biodiesel as prescribed in the ASTM D6751 standard is 0.05% vol., and high moisture content in biodiesel could cause problems like water accumulation and microbial growth during fuel handling, storage, and transportation [54]. Higher water content in biodiesel will either increase the corrosion rate of metallic engine parts or form an emulsion that could block the fuel supply system [79]. The problems of water in biodiesel are often due to poor biodiesel treatment after processing, or as a result of the occurrence of intensive microbial activity in biodiesel, and absorption of atmospheric moisture during storage [54, 79]. The hygroscopic nature of biodiesel makes the moisture content of biodiesel increase over time during storage, and as part of the measures designed to tackle this problem, Kolobeng et al. [80] and Dadan and Shiro [12] recommended that the moisture threshold of 0.5 mg/g specified for biodiesel by the ASTM D2709 should be maintained during the entire storage time of biodiesel by blending it with petroleum diesel in order to delay biodiesel degradation, increase the life span of the biodiesel, and ensure good quality. The determination of the optimal moisture content in an oil is critical for the optimization of biodiesel yield in the alkali transesterification process. Chemg-Yuan and Lei [79] reported that a moisture content of 0.05 wt.% in raw oil was the optimum quantity to produce palm oil biodiesel with superior fuel structure of fatty acids, burning characteristics, and yield. A higher or lower moisture content than 0.05 wt.% would lead to slower nucleophilic substitution reactions, and hence a lower conversion rate from raw oil, in addition to deteriorated burning characteristics. Besides, moisture in biodiesel could lead to the formation of emulsion, which may block the fuel supply system [79]. Furthermore, it is reported in Ref. [79] that water content in palm oil biodiesels increased with the increase of storage temperatures and storage time, leading to the degradation of fuel properties. Electrochemical impedance spectroscopy has been developed for the determination of the water content in biodiesel [79].

1.8 Calorific value

The calorific value of a fuel, often referred to as the heating value, represents the energy content of the fuel. The calorific value of a fuel is the amount of heat energy released when a unit mass of the fuel is combusted or burned completely in a sufficient amount of air. The calorific value, or heating value, can be used to distinguish between different fuels in terms of their capacities to produce more or less power or torque per unit volume. It is used to compare the energy content per liter of the various fuels being considered. Zammit [49] reported that fuels containing hydrogen have two calorific values—the higher, or gross calorific value (HCV), and the lower, or net calorific value (LCV). The higher calorific value represents the energy released from the complete combustion of the unit mass of the fuel when the products of combustion are cooled to the original temperature of the fuel. The difference between the lower calorific value and the higher calorific value lies in the latent heat of the vaporization of steam for every fuel. Singh [81] reported that biodiesels have lesser heating values than that of fossil diesel, because in biodiesels, carbon and hydrogen are the sources of thermal energy, while oxygen is considered as ballast. Biodiesel is reported to contain between 9% and 10% oxygen and hence, the reason biodiesel is often considered an oxygenated fuel, in comparison to the 3% found in fossil diesel [14, 81]. This development makes biodiesel have lower heating values than fossil diesel, but with higher combustion efficiency, with a reduction in particulate matter (PM), Carbon Monoxide (CO), and other gaseous pollutants than fossil diesel, due to the higher oxygen content of biodiesel [14, 81, 82]. Knothe et al. [83] observed that this is also the reason why biodiesels have a lower stoichiometric air/fuel ratio than that of conventional diesel because less air will be required to burn biodiesels compared to conventional diesel, and concluded that it is also for this reason that biodiesel-fueled engines are reported to emit about 10% higher NO_x emissions than fossil diesel fuel engines [14, 83]. The combustion of biodiesel does not result in increased atmospheric carbon dioxide [14], but high emissions of oxides of nitrogen (NO_x) are also associated with biodiesels of low heating value [27]. Nonetheless, since the conversion of oil to biodiesel does significantly affect the calorific values of oils, with the degree of impact depending on the catalyst employed, it means that oils with very low calorific values would not be economically viable for biodiesel production. However, oil with low oxygen content will be a better choice for biodiesel production for greater energy delivery. Zammit [49] observed that the variations in biodiesel energy density depend much more on the feedstock used than the biodiesel production process. The bomb calorimeter is used for the experimental determination of the calorific value of a liquid fuel. The calorific value of most biodiesel obtained from vegetable oils and animal fats ranges from 37.27 to 41 MJ/kg, which is lower than the 45.5 MJ/kg and 42 MJ/kg reported for conventional diesel fuel and oil, respectively. Kipkorir et al. [27] reported that the heating values of pure biodiesel, pure fossil diesel, and distilled engine oil are 39.61 MJ/kg, 42.63 MJ/kg, and 41.9 MJ/kg, respectively. Biodiesels with much lower calorific values are better used for blending diesel fuels.

1.9 Cetane number

This is an important property of diesel fuel, and it is one of the measures of fuel quality that helps in determining whether a diesel fuel will be suitable for use in a diesel compression ignition engine or not. It is a measure of the readiness or tendency of diesel fuel to autoignition, or "knocking" [19, 48, 49]. The cetane number is an indication of the ignition performance quality of a liquid fuel or oil, and it is obtained by comparing the cetane number (CN) of fuel to reference fuels in a standardized engine test. There is a direct relationship between the cetane number of fuel and the ignition delay time (i.e., the time between the start of injection and the start of combustion) of the engine. When the cetane number increases, the ignition delay decreases and the combustion phase increases. A long ignition delay has negative consequences as it causes diesel knock. When the cetane number of diesel fuel is too high, the fuel will pre-ignite close to the injector and lead to excessive heating of the injector, resulting in "cooked fuel particles" in the injector, which may plug the injector nozzle [19]. Zammit [49] observed that the higher the cetane number of any fuel (60–70), the better the suitability and performance of the fuel for compression ignition work output. However, an increased cetane number of biodiesel usually leads to advanced combustion by reducing the ignition delay, and this ultimately decreases the time for the premixing of fuel and air before combustion [48]. Though a low cetane number is not suitable for a diesel engine, too high a cetane number is equally counterproductive. As is the case with other fuels, biodiesel fuel with too low or too high cetane number will lead to engine problems [19, 48, 49]. Chhetri [34] reported that the cetane index of waste cooking oil is 61, while Hilber et al. [84] indicated that the cetane numbers of methyl esters of rapeseed oil, soybean oil, palm oil, lard, and beef tallow are 58, 53, 65, 65, and 75, respectively. Of all the above-listed biodiesel feedstocks, the higher cetane number of beef tallow implies that its biodiesel will have a higher engine performance in comparison to other fuels, thereby resulting in lower emissions of all pollutants except the oxides of nitrogen (NO_x) and carbon dioxide (CO_2) [85]. The high cetane number of beef tallows has been linked to its higher saturated fatty acid content, and the increased amount of saturated fatty acid content in oil feedstock has been found to have positive effect on the cetane number of biodiesel produced from such oils or fats. Additionally, the presence of a very high amount of saturated fatty acids in biodiesels has been found to improve the oxidative stability of such biodiesel fuels. However, one major drawback arising from having a very high amount of saturated fatty acid content in biodiesel fuel is that it usually raises the cold filter plugging point (CFPP) temperature of the biodiesel [34]. The cetane number of any biodiesel is highly dependent on the feedstock from which it is produced, with increasing cetane number leading to a reduction in the ignition delay of the fuel as stated before. Biodiesels usually have a higher cetane number, except for those of corn and olive methyl esters, when compared with those of fossil diesel fuel, and consequently, a shorter ignition delay than diesel fuel, and this has been attributed to the existence of a higher amount of oxygen in the structure of biodiesels [33, 86]. Demirbas [86] observed that biodiesel is largely composed of long-chain hydrocarbon groups with virtually no branching or aromatic structures, and the longer the fatty acid carbon chains, the more saturated the molecules and the higher the cetane number. Biodiesel fuels from feedstocks with long carbon chains and more saturated fatty acids, like fats or waste greases, have higher cetane numbers than those of biodiesel produced from vegetable oils [19]. The ignition delay (ID) of engines has been linked with the cetane number of diesels, with a shorter ignition delay corresponding to a higher cetane number and vice versa. Diesel fuels with higher cetane numbers will ignite at lower temperatures and have a very short ignition delay. If the periods between the injection of fuel and the start of the ignition take too long (low CN), a strong diesel knock usually occurs, leading to engine misfiring. When the cetane number is too high, combustion can occur before the fuel and air, are properly mixed, resulting in incomplete combustion and thick smoke [86]. Canakci and Sanli [19] observed that the transesterification of vegetable oils to biodiesel does not impact negatively on the cetane number of the oil. The cetane number of biodiesel is determined based on the ASTM D613 standard. The ASTM D6751 stipulates that the minimum cetane number of biodiesel fuel suitable for diesel engines should be 47.

1.10 Cloud point

This is one of the important parameters that help in determining the fuel flow performance in any automobile engine system. The environmental temperature strongly affects the viscosity of oils, and it is inversely proportional to the viscosity of any given oil. Compression ignition engines are difficult to operate at low temperatures, especially in cold climate regions, owing to high viscosities. Ayetor et al. [33] posited that this is why low-temperature properties of oils and biodiesel fuels are necessary in order to determine the feasibility of use, or otherwise, in cold climate countries. The cloud point of oils or fuel is the temperature at which cloud wax crystals first appear in the oil or fuel when it is cooled under the conditions prescribed in ASTM D2500. The cloud point is usually visible to the naked eye. The formed crystals can plug the fuel lines and filters and cause operational problems to the engine fuel system [19]. The cloud point of biodiesel depends upon the oil feedstock from which it is produced, and it is one of the cold properties of any fuel that must be taken into consideration if the diesel fuel is to be used in cold environments. Akhil [87] reported that the cloud point of any oil indicates the tendency of such oil to plug filters or small orifices at cold operating temperatures. Hence the cloud point tells us a lot about the suitability of lubricating oils and fuels for engine operations in cold conditions. Oils with very high cloud point will yield biodiesels with high cloud point, and such biodiesels can only be used for blending purposes or else will require additional expensive treatments by way of the addition of additives before they can be used in diesel engines in different environments. The cloud point of any oil has been found to occur at a higher temperature than the corresponding pour point of the oil, and the same holds for that of its biodiesel. The cloud point of biodiesel is reported to be higher than that of fossil diesel fuel, and this usually restricts the utilization of biodiesel fuels in the cold season [19, 32, 87–89]. It is reported in Ref. [32] that the cloud point of most biodiesels is within the range of −20°C to 284°C according to the ENISO3016 standard. Cloud point is one of the temperature-dependent parameters determining the use of biodiesel in different geographical and climatic conditions. The ASTM D6751 standard did not specify any allowable limit for cloud point, because this parameter is unique for every climatic condition in each geographical region. Chhetari et al. [34] reported that the saturated fatty acid chain determines to a very large extent the cold-flow properties of biodiesel fuels. The freezing point of a biodiesel fuel increases with increasing carbon atoms in the carbon chain and decreases with increasing double bonds, and hence, biodiesel from feedstocks with a large number of saturated fatty acids has higher cloud points and pour points. And these explain why biodiesel from vegetable oil has lower cloud and pour points than that obtained from fats and greases [19]. Hilber et al. [84] have developed a relationship between the cold properties of biodiesel and the saturated fatty acid chain. They observed that the cold filter plugging point (CFPP) of biodiesel occurs at higher temperatures as the saturated fatty acid levels increase. Oils with less saturated fatty acids usually perform better than fats or other oils containing higher amounts of saturated fatty acid chains. The CFPP range for animal fats is from 12°C to −1°C, while that for rapeseed oil is from −7°C to −12°C [84]. Furthermore, the CFPP for waste cooking oil as reported by Chhetri et al. [34] is −10°C. Lee et al. [90] pointed out that whereas the cloud points of oils and biodiesels are affected by the presence of monoglycerides, their pour points are not affected by the monoglycerides. Chhetri et al. [34] reported that the cloud point of ethyl esters, or biodiesels, is approximately 2°C lower than that of their corresponding methyl esters, to the effect that the ethyl esters will perform better in cold temperatures than the corresponding methyl esters. Chhetri [34] determined the cloud point of ethyl ester produced from waste cooking oil to be −1°C. The differences in cloud point of ethyl esters and methyl esters produced from the same oil have been presented in Ref. [34].

1.11 Pour point

This is another important parameter that helps in the assessment of the cold-flow properties of liquid fuels at different temperatures. The pour point of oil or fuel is the temperature at which the oil or fuel becomes semi-solid and loses its flow characteristics or ceases to flow anymore when it is cooled. The pour point of any liquid usually occurs at a lower temperature than the cloud point of the same liquid. The pour point of feedstock oil is usually higher than that of the biodiesel produced from the oil. The pour point of biodiesel is usually higher than that of conventional diesel fuel, and this is the reason why some biodiesel is considered unsuitable for use in the cold season. The pour point indicates the temperature below which oil cannot be used as a lubricant anymore [87]. The conditions specified for the determination of the pour point of biodiesel are specified in the ASTM D97 standard, while the ASTM D6751 prescribes that the standard pour point of a quality biodiesel fuel should be in the range of −15°C to −16°C [32]. Using fuel at a temperature below its pour point will bring down the performance of the engine. Alptekin [91] reported that the pour point of biodiesel is independent of both the type of catalyst and reaction conditions but rather depends on the amount of saturated fatty acids in the oil. The cis-double in some oil usually hinders the lowering of the pour point of esters. Furthermore, the type of fatty acid branched-chain operating in the original oil has a significant impact on the pour point of the oil. High unsaturation (high iodine number) leads to poor oxidative stability, which is highly undesirable in biodiesel for optimal performance. It is reported that better cold-flow behavior by biodiesel was exhibited by oils with a higher degree of unsaturation, longer chain length, a higher degree of branching, and cis configuration [2, 92]. The addition of more complex alcohols, like isobutanol in the transesterification reaction increases the carbon chains to the biodiesel esters, resulting in lower freezing temperatures [2, 19, 93]. Though branched-chain alcohols are less reactive, they have been reported to improve the cold-flow quality of biodiesels, but their reactions result in significant amounts of impurities of monoglycerides, diglycerides, and triglycerides, which are the signs of incomplete transesterification, with these impurities likely to cause engine operation problems [19]. Besides, these alcohols have a higher tendency for water absorption during the washing process with methanol. Furthermore, branched-chain alcohols are usually expensive and hence are not economically viable. Additionally, the fact that these branched-chain alcohols require much more alcohol, with ratios as high as 70:1, and with their high molecular weights, the production cost rises with the attendant lower yields [19]. Chhetri [34] reported that the pour point of the biodiesel produced from waste cooking oil was −16°C. Biodiesels from greases have better cold-flow properties than those from tallow esters because greases are mixtures of fats and oils. The differences in the pour point of ethyl esters and methyl esters, produced from the same oil, are presented in [34].

1.12 Oxidation stability

This is an important parameter that indicates the resistance of oils or fuel to oxidation during prolonged or extended periods of storage. It is a measure of the duration of time or shelf life of oils or fuel before they degrade by getting oxidized by atmospheric oxygen to form undesirable products with the capacity to damage an engine [19, 74]. Oxidation stability determines the usefulness of edible vegetable oils in technological processes as well as their shelf life [94]. Storage stability is one of the major criteria for assessing the quality of biodiesel. The storage of oils or biodiesel for extended periods may lead to the degradation of the properties of the substances. The degree of unsaturation determines the extent of susceptibility of vegetable oil derivatives to thermal or oxidative polymerization, which often results in the formation of insoluble products that cause problems in the fuel system [14]. Ordinary temperature oxidation of oils and even biodiesels produces hydroperoxides, which then yield peroxides that split, later releasing aldehydes, ketones, and short-chain acids that give foul odors [19]. This oxidation process makes oils and fuels deteriorate and lose their essential properties, leading to the formation of gum. Gum does not combust completely; as a result, it usually leaves carbon deposits in the combustion chamber, which also thickens the engine lubrication oil [14, 19]. The oxidation oil makes them become more viscous and much more expensive to produce biodiesel from. Moreover, when biodiesel oxidizes, its cetane number increases due to the increased viscosity as a result of oxidation with time. The oxidative stability of any liquid fuel is determined via the copper strip test since copper has the strongest catalyzing effect on oxidation. The oxidative stability of biodiesel is not dependent on the total number of double bonds but on the total number of bis-allylic sites in the biodiesel [14]. An oxidized biodiesel will burn with a shorter ignition delay than the unoxidized one, producing increased NO_x emissions [19]. The factors that impact the oxidative stability of edible oils include temperature, light, oxygen concentration, oil processing, and fatty acid composition [95]. However, one important factor that plays a major role in the oxidation process is the chemical structure of the oil or biodiesel [14, 19, 95]. The oxidative stability of oils, or even biodiesel, decreases with decreasing molecular weight, increasing amount of double bonds present, and number of double bonds per molecule [14]. The presence of double bonds in the chains of oil feedstock makes the oil unstable [19]. Feedstocks with a higher proportion of saturated fatty acids are more stable than those with a higher proportion of unsaturated fatty acids. However, a higher proportion of saturated fatty acids raises cloud and pour points. Determining the appropriate balance between the level of saturation of biodiesel and its cold-flow properties is critical in selecting oils for biodiesel production. Oil feedstocks that are rich in polyunsaturated fatty acids are more liable to oxidation than feedstocks that are rich in monounsaturated and saturated fatty acids [19, 74]. The methyl esters of oils that are less saturated tend to have higher oxidation rates, as the relative oxidation rates of the basic fatty acids in oils show that while the oxidation rate of the oleates is 1, those for linoleates and linolenates are 41 and 98 times higher, respectively [19, 94]. Degradation of biodiesel has been found to be accelerated by the presence of the following: oxygen, water, heat, and impurities. The degradation of biodiesel often leads to the formation of corrosive products like acids, which interact negatively with fuel injection equipment to form insoluble gums and sediments that could plug fuel filters. The autoxidation reaction rate depends on hydrocarbon structure, heteroatom concentration, heteroatom speciation, oxygen concentration, and temperature [14]. Biodiesel derived from waste frying oil has been found to have lower oxidative stability due to thermal process [14]. The most reliable test for the determination of the oxidative stability of oils is the storage test, but this is very time-consuming. Hence, the most frequently used methods include the Rancimat test, the Schaal Oven Test (thermostatic test), and chemical determinations of peroxide value, anisidine value, and acid value [94].

1.13 Iodine value

This is one of the parameters that need to be monitored and evaluated if the integrity of the oils and biodiesel produced and distributed in the market is to be guaranteed. The determination of the iodine values of oil for the production of biodiesel is useful for effective quality control during the biodiesel production process. Iodine value of oil or biodiesel represents the mass of iodine in grams that is consumed by 100 g of the oil or biodiesel. The iodine value, or number, is often used to determine the degree of unsaturation (number of double bonds) in fats, oils, and waxes because it has been found to be proportional to the degree of unsaturation of these products, and it indicates its oxidative stability [14, 17, 71]. Unsaturation occurs in fatty acids due to the presence of double bonds in this compound, which are the major cause of instability in vegetable oils, as they are very reactive toward halogens like iodine [14]. Thomas [96] observed that the higher the iodine value of any oil or fat, the more the degree of unsaturation of the oil or fat. Vegetable oils are known to contain polyunsaturated fatty acids that are highly unsaturated. Oils with high iodine values contain more of these highly unsaturated fatty acids that are susceptible to fast degradation reactions such as autoxidation or polymerization [17, 97]. The more iodine absorbed by any oil, fat, or wax, the higher the iodine value, and the more reactive, less stable, softer, and more prone to oxidation and rancidification the oil, fat, or wax will be [65]. A low iodine value of below 100 mg/100 g is an indication that the oil is non-drying [61]. Oils with low iodine value, like coconut oil, which are very saturated, are good for soap making, while highly unsaturated oils, like linseed, which are also drying oils, are very suitable for making oil paints [71, 96]. The iodine values of non-drying oils are below 100, and the contact of these oils with oxygen does not cause any appreciable drying of the oils. Tanks containing non-drying oils are easy to clean. Testing the iodine value of feedstock oil is essential, mainly for monitoring the level of degradation of the oil. Banga and Varshney [14] identified the major causes of instability in biodiesel to include the position and number of double bonds per molecule of vegetable oil, esterification efficiency, free acids, glycerols, and partially transesterified oils. The levels of unsaturates and polyunsaturates in oils can be reduced by hydrotreating as well as the use of antioxidants to prevent reactions of unsaturates in fuels by inhibiting or interrupting oxidation and polymerization reactions, thereby preventing degradation, oxidation, and gum formation [14]. Seneviratne and Jayathilaka [98] have provided a table showing the iodine values of some common crops together with the percentage of double bonds contained in the oil. They assumed that the maximum percentage of double bonds of 300% is given by an oil containing triglycerides with 100% of linoleic acid. The conventional method for the determination of the iodine value of oils or biodiesel is the titration of the excess halogen reagent with a sodium thiosulfate solution (Wijs reagent). However, other methods like the flow-based procedure and the quantitative spot test have also been used by some researchers for the determination of the iodine value of liquid samples [71]. The ASTM-525 and ASTM 6418 tests are used for measuring the thermal stability of biodiesel by quantifying the extent of color degradation and gum formation, respectively, while long-term storage tests like ASTM D-4625 have been used to determine oxidation stability. The effects of aging in long-term storage tests are measured by changes in viscosity, which usually increase with time [14]. The ASTM D6751 did not specify any limits for the iodine value of biodiesel fuels.

1.14 Peroxide value

The peroxide value (PV) is often used as a key indicator of the rancidity of lipids, as a quality indicator, and as an indicator of the shelf life of lipids. Peroxide value measures the concentration of peroxides and hydroperoxides formed during the initial stages of fat and oil oxidation. When unsaturated fatty acids come in contact with oxygen, they form peroxides that lead to rancidity, discoloration, and changes in the physical properties of the oil [99]. The peroxide measures the amount of reactive oxygen content of a liquid expressed in terms of milliequivalent (meq) of free iodine per kilogram of fat or oil, and the peroxide value is determined by titrating iodine liberated from potassium iodide with sodium thiosulfate solution. A high peroxide value for any oil indicates deterioration of the oil. Oils with a peroxide value of less than 10 meq/kg are considered fresh oils, while a rancid taste begins to be noticeable when the peroxide value of the oil is between 20 and 40 meq/kg. Peroxides are the precursors of broken-down products that cause rancid flavors in fats. Unsaturated oils are susceptible to oxidation, and these oils usually develop peroxides under poor cold storage or frozen storage conditions. Rocha et al. [71] observed that the concentration of peroxides in oil is indicative of the oxidation state during the early stages of lipid deterioration. However, they concluded that this index is not reliable during the later stage of deterioration, as peroxide degradation increases with time. Rancidity is the process by which fats and oils in food become degraded, resulting in off-odor/flavor, taste, and texture. Rancidity is caused by the oxidation of unsaturated fatty acids and is usually accelerated by such factors as exposure to light, heat, and air. Whenever any oil becomes rancid, its long-chain fatty acids will become broken down, into short-chain compounds and become degraded [99]. Oils with very high peroxide values will not be economically viable for the production of biodiesel. Both the oil and even the converted biodiesel have a high tendency to break down, deteriorate, and lose their vital physical properties.

1.15 Refractive index

This is an important optical parameter used to analyze light rays traversing through a material medium. It indicates the level of optical clarity of a vegetable oil sample in comparison with water [17]. The refractive index is a parameter that is related to the molecular weight, fatty acid chain length, degree of unsaturation, and degree of conjugation [54]. It is a property that allows for the evaluation and determination of the predominant ester's degree of saturation. As a characterization tool, it can indicate the possible chances of rancidity development in oil. The higher the refractive index of oil or fat, the greater the chances of spoilage due to oxidation [31]. The refractive index is a reliable physical property that has been used to predict transesterification reaction progress. Even the density and viscosity of biodiesel blends have been predicted using the refractive index of the blend [100]. Nita et al. [100] used the Wiener, Heller, and Edward equations to predict with great accuracy the refractive index of conventional diesel fuel + biodiesel blends. Furthermore, Alviso et al. [31] reported that olive and peanut biodiesel have the lowest refractive indexes of 1.4443 and 1.4448, respectively, while soybean and grape biodiesel have the highest refractive indexes of 1.4495 and 1.4500, respectively. Moreover, the refractive index has also been used to monitor and predict the progress in the conversion of oils to biodiesel (transesterification reaction) as well as to track the stability of biodiesel in an accelerated oxidation process and even in biodiesel combustion studies [31, 100]. Vegetable oils and fats with high refractive index should be handled with great care and urgency as they have a high susceptibility to deterioration and degradation. Degraded oils and fats will not produce good quality and high yield of biodiesel.

2. Conclusion

This chapter has tried to present the essential properties of the feedstock oils required for the viable production of biodiesel and the impacts of the properties on the behavior of the produced biodiesel. Biodiesel has proved to be a promising alternative to conventional diesel. However, the greatest challenge to the attainment of the goal of the commercialization of biodiesel lies in the cost of biodiesel production, which is high in comparison to that of conventional petroleum diesel. This state of affairs has made imperative the need for the identification of the various essential parameters in feedstock oils that lend the oils to quality biodiesel production and improved yield, with a view to optimizing the biodiesel production processes in order to obtain increased production yield, improved product quality at the least possible cost, minimize waste, and improve the marketability and market share of biodiesel fuels in the global energy sector. Many research reports have attributed the limitations to the commercialization of biodiesel for diesel engine use globally to its high cost of production. One of the suggested solutions for reducing the market price of biodiesel is the analysis of the feedstock oils or fats prior to conversion to biodiesel, with a view to determining whether the oils or fats possess the right physicochemical properties that lend them to the production of good quality and high yield of biodiesel, in addition to serving as a guide for selecting the best combination of reactants as well as the most economical method to be adopted for the biodiesel production process for each given raw material feedstock.

In this quest for bringing down the cost of production of biodiesel, the identification and selection of the right oil feedstocks, and matching them with the most suitable reactants remain the key strategy. Studies have shown that the use of high-quality vegetable oils will yield high-quality biodiesel but with a higher cost of production per liter than producing biodiesel from less expensive feedstocks such as waste frying oils, soapstocks, fats, and greases [19]. However, the challenge of utilizing these less expensive feedstocks lies in the fact that they contain high amounts of FFAs, to which the direct application of transesterification has not proven to be very efficient and economical [14, 19, 20, 34, 47], though high yields and reaction rates have been recently achieved with heterogeneous catalysts [24]. Furthermore, enzymatic catalysts like lipases are reported to be more efficient in the transesterification of triglycerides but the cost of the catalyst production is very, very high. Furthermore, the cold properties of the biodiesel produced from the low-cost feedstocks have not been encouraging, as many of them, especially fats, have been found to have high levels of saturation [19, 20]. The major impurities in biodiesels are glycerol, residual catalyst, excess alcohol and metals, unconverted/partly converted fat, and soap [14, 18, 25], as well as sterols and polar lipids [4]. The strategy of using branched-chain alcohols in the transesterification process for converting oils to biodiesel has significantly improved the cold-flow properties of the biodiesels produced from the low-cost oil feedstocks.

Finally, while it is true that the performance of biodiesel depends on its purity and the cleanliness of the final product, without contaminants, it is very important to focus on improving the cold-flow properties of the biodiesels obtained from the low-cost oil feedstocks. Moreover, it is equally inevitable to continue to search for better combinations of the biodiesel production parameters in order to achieve high-quality biodiesel and increased yield from every abundantly available oil feedstock. In this regard, the use of heterogeneous catalysts seems to be very promising as a way forward in the quest for obtaining increased biodiesel yield of good quality at reduced cost, since it has been reported that heterogeneous catalysts are more efficient in transesterification of high FFA, especially for non-edible oils than the homogeneous catalysts [14, 18, 24]. Therefore, as part of the strategy toward bringing down the production cost of biodiesels from oils and fats, it is vital that the essential properties of oils are first determined to guide the selection of the right feedstocks for biodiesel production in order to guarantee viability, quality, optimal yield, and improved cost reduction in the production of biodiesel fuels that can compete favorably cost-wise, with the conventional diesel fuel in the global market. The characterization of oil will aid in driving research toward improving the fuel properties limitations of biodiesel, which impact negatively the engine performance characteristics in diesel engines, and tries to reduce the cost of addressing them.

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Chapter 4

Biodiesel Production Potential in Sustainable Biomass Diversity

Ahmet Karadağ, Özgenur Dinçer Şahan, Attia Hamid and Muhammad Nauman Aftab

Abstract

Selecting suitable feedstock oils is essential for cost-effective biodiesel production. Research is focused on non-food oils such as *Jatropha, Karanja*, and animal fats. Karanja contains 27.5% fat, while Jatropha has non-edible fat content of 38–40%. Industrial hemp seeds (*Cannabis sativa*) also stand out, with an oil content of about 30–35%. Additionally, microalgae, which absorb CO_2 and help reduce greenhouse gases, are an appealing biodiesel source. Biodiesel production also utilizes oils derived from soybeans (7%), sunflowers (3%), palm oil (15%), rapeseed oil (47%), canola oil, and cottonseed. Other significant biodiesel feedstocks in the United States include animal fats sourced from meat processing plants, used (recycled) cooking oil, and yellow grease (18%) from restaurants, as well as animal fats (8%). Yellow grease is specifically employed in biofuel production. This diversity is crucial in the selection of feedstocks for biodiesel production, considering sustainability, especially in terms of whether they are primary food sources or not, and taking into account the variety and oil content of bioenergy feedstocks. The physical (macro-scale), structural (micro-scale), and compositional (molecular-scale) characteristics of feedstock types, in addition to their lipid content, are crucial in biodiesel production, influencing conversion efficiency and process economics.

Keywords: biofuel, biodiesel, bio raw material, feedstock oils, sustainable

1. Introduction

The global energy demand is increasing rapidly due to swift population growth and concurrent economic expansion. Meeting energy needs using fossil fuels presents significant challenges. Consequently, there is a worldwide surge in demand for biofuel production and the utilization of green energy resources. Biodiesel, a prominent biofuel, holds the potential to supplant fossil fuels. Green energy sources are possible alternatives to petroleum diesel [1]. Therefore, biodiesel production continues to increase day by day worldwide (**Figure 1**).

The energy crisis prompted by rapid population growth and the gradual depletion of fossil petroleum fuels has led to increased production of biodiesel as an alternative to fossil diesel. With this aspect, biodiesel is on its way to becoming an adopted and

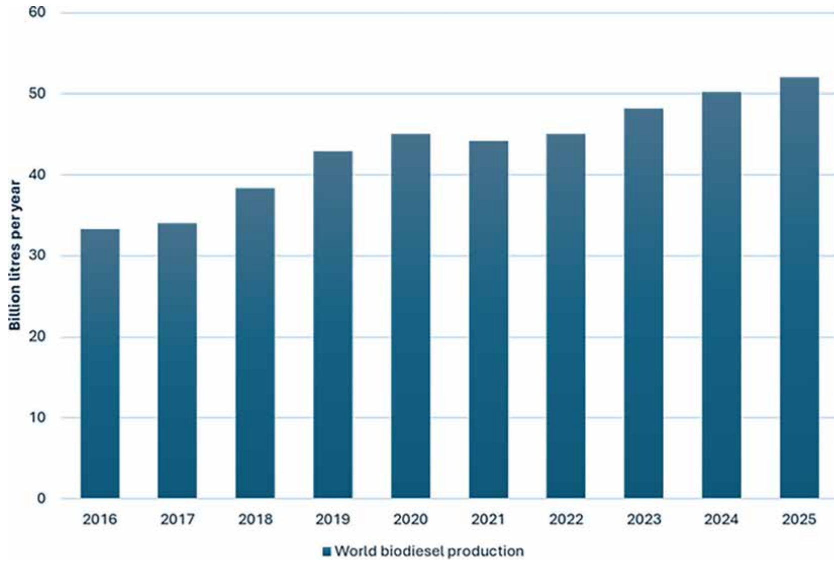

Figure 1.
Global biodiesel production [2].

important fuel in many sectors [3]. Compared to petro diesel, biodiesel emits 50% less smoke, 30% less carbon monoxide, and 20% fewer hydrocarbons [4]. Additionally, biodiesel is appealing due to its lower sulfur content, higher cetane number, and flash point exceeding 130°C compared to petroleum diesel. The widespread use of biodiesel as an alternative fuel is gaining momentum due to its oil content, renewability, and compatibility with existing diesel engines.

Biodiesel is a blend of vegetable or animal oils and a solvent, typically produced by reacting a short-chain alcohol (such as ethanol or methanol) with a catalyst (either basic or acidic). Chemically, biodiesel is known as fatty acid methyl esters (FAMEs) [5, 6]. It can be produced from various raw materials, including both edible and nonedible oils, as well as oils derived from waste sources [7].

The content of FAMEs in biodiesel includes stearic acid, palmitic acid, linoleic acid, oleic acid, behenic acid, and arachidic acid. These acids are derived from suitable raw materials, reflecting the components of those materials in the final biodiesel product [8]. Critical parameters for the production and utilization of biodiesel include density, oxidation stability, and viscosity. Additionally, properties such as metal content, water content, and triglyceride levels vary based on production parameters and postproduction processes.

Utilizing biodiesel instead of petroleum diesel results in lower emissions of carbon monoxide (CO), hydrocarbons, particulate matter, aldehydes, and nitrogen and sulfur oxides. Biodiesel's high biodegradability reduces its environmental impact, and it does not pose health risks as it lacks carcinogenic compounds. Moreover, biodiesel burns efficiently and can be blended with conventional diesel in any proportion for use in transportation without requiring engine modifications [9]. When compared to waste plastic oil, tire pyrolysis oil, and biomass pyrolysis oil, biodiesel demonstrates superior combustion properties. The advantages and disadvantages of biodiesel are detailed in **Table 1**.

There are numerous plant species that serve as raw material sources for biofuel production. Biofuel feedstocks can produce oil for biodiesel, while also yielding sugar and starch that can be converted into bioethanol and biobutanol. These diverse biofuel sources, such as camellia, sugarcane, corn, algae, Karanja oil, and canola oil, are essential for producing various biofuels including ethanol and biodiesel. Key applications of these feedstocks encompass agricultural products, byproducts, biofuels and bioenergy, biodiesel production, anaerobic digestion, nutrient cycling, renewable energy, and municipal waste management [10].

The raw material sources for biodiesel production can be categorized into three generations.

First-generation raw materials include plant oils typically used for food purposes, such as rapeseed, sunflower, palm, and soybean oils. However, the use of these oils presents ethical issues since they are vital food sources. Large-scale biodiesel production from these oils can disrupt food supply chains, inflate market prices, and is not sustainable [11].

Second-generation raw materials address the need for sustainable sources by utilizing non-food-based materials such as waste oils, used cooking oils, greases, waste animal fats, and agricultural residues not meant for consumption [12]. These raw materials are advantageous due to their low cost, sustainability, and minimal environmental impact.

Advantage	Disadvantage
Fossil fuels will eventually run out, but biodiesel is a renewable fuel source.	Today, biodiesel is considerably more expensive than petroleum diesel.
Since it has the ability to work well in engines, it provides the opportunity to use it without any changes in vehicles.	It removes dirt from the biodiesel fuel filter, and this dirt can clog the filter and damage the vehicle engine. Filters need to be checked regularly.
It can be stored in the same tanks where diesel oil is stored.	If it is produced from sources of raw materials used as food, it can damage the food supply, causing famine.
The risk of biodiesel, which is produced from various raw material sources, is considerably lower than petroleum diesel.	It can be difficult to use at low temperatures.
When bulk production will be made, the cost will be low.	
The power performance is quite good.	
Since it reduces CO_2 and HC (hydrocarbon) emissions, it reduces environmental pollution and improves human health.	
The use of second-generation raw material resources or waste oils prevents environmental pollution.	
Compared to petroleum diesel, its flammability is low.	
Its lubrication is better than petroleum diesel.	
Since the raw material sources used are produced from animal and plant sources, they are biodegradable and have no toxic properties.	

Table 1.
Advantages and disadvantages of biodiesel.

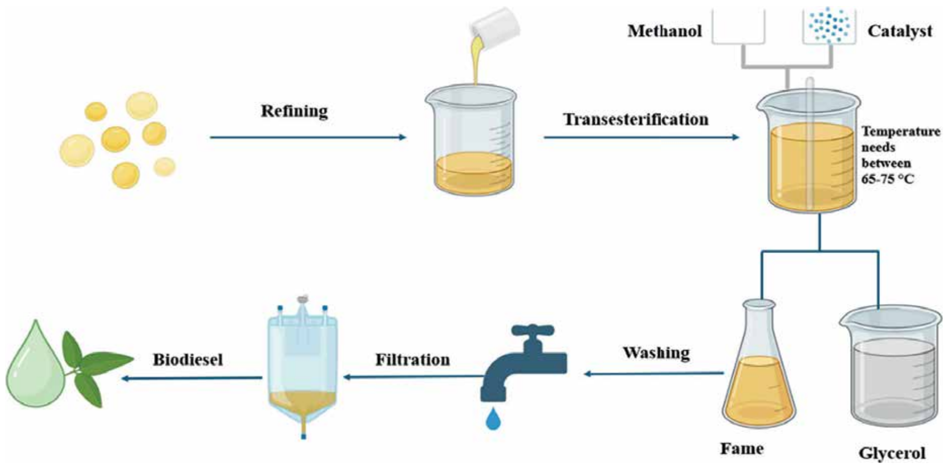

Figure 2.
Proses of biodiesel production.

Third-generation raw materials focus on the use of algae for biodiesel production. Regardless of the raw material source, the physical and chemical properties of biodiesel remain consistent [13].

In (**Figure 2**), the production stages of biodiesel originating from a feedstock are shown schematically.

2. Main feedstock's, intrinsic characteristics, and generated biofuel quantities

2.1 Sugar and starch crops

Currently, the processing of agricultural resources into starch and sugar products enables their use as raw materials in fermentation. This practice is not anticipated to change due to the low cost of using lignocellulosic biomass. Converting starch into glucose *via* enzymatic or chemical methods is significantly easier than converting cellulose. The enzymatic method, which involves starch liquefaction and hydrolysis by enzymes, is extensively utilized in the corn refining industry. In the United States, approximately 22% of the 300 million metric tons of high-quality corn produced annually is used to produce high-fructose corn syrup, dextrose, starch, and fuel alcohol. Dextrose, or glucose, the building block of starch, is the primary substrate for industrial fermentation in the United States. In 2023, around 4.18 billion bushels of ethanol were produced from 13.64 billion bushels of corn [14]. Additionally, sucrose derived from sugar beet and sugar cane is the main fermentation substrate in other countries. Grains and their processed derivatives are primarily used for food and animal feed, with only a small portion allocated for biofuel, chemical, and industrial product production [15]. However, global data indicates a substantial amount of crop residues available for fermentation raw materials: sugar cane bagasse at 180 million tons, rice straw at 731 million tons, corn stover at 204 million tons, and wheat straw at 354 million tons. Starch plants such as wheat, corn, barley, rye, potatoes, and cassava are commonly used to convert starch into sugar.

The raw materials of the plants frequently used for sugar production in the world are sugar cane and beet. Two-thirds of the world's sugar production using raw materials comes from sugar cane, while one-third comes from sugar beets [16]. It can be hydrolyzed by the invertase enzyme synthesized by most Saccharomyces species. Therefore, there is no need for pretreatment for the production of bioethanol from raw materials containing sugar (sucrose), which means that this method is more suitable than raw materials containing starch. Plants used for sugar production undergo only a grinding process to extract the sugars into the fermentation medium; in this way, ethanol can be produced directly from fruit juice or molasses [17].

Sugarcane, a semi- and perennial crop, offers several advantages for bioethanol production. It does not require agricultural processing in its raw form, can be used as biomass to produce heat and electricity generation, has high efficiency, and is more cost-effective compared to other raw materials. Efforts to enhance bioethanol production from sugarcane include developing varieties with higher sugar content, increased disease resistance, greater biomass yield per hectare, and longer lifespans [18].

In Europe, sugar production primarily relies on sugar beet as a raw material. During sugar beet processing, high-purity crystalline sugar is produced, along with intermediate materials like raw, fine, and dark fruit juice, which can be converted into bioethanol or bio-based products. Additionally, raw sugar beet cassettes serve as suitable substrates for bioethanol production [19, 20].

Molasses, a primary by-product of sugar beet and sugarcane processing, serves as a significant substrate for producing yeast, bioethanol, biochemical products, and animal feed [21]. Analyzing molasses content reveals that the total residual sugar amounts to approximately 50–60% (m/V), with sucrose comprising around 60% of this total. This substrate is extensively utilized for large-scale bioethanol production. Cane and beet molasses, byproducts of sugarcane and sugar beet, respectively, are employed to extract and refine sucrose. Cane molasses contains about 46% total sugar, while beet molasses has approximately 48% (m/V) total sugar. Additionally, molasses derived from citrus pulp exhibits a total sugar content of around 45% (m/V). The production of glucose from starch, derived from corn or grain sorghum through enzymatic or acid hydrolysis, also generates molasses. Starch molasses has a sugar content of approximately 43% (m/V) and a total solids content of around 73% (m/V) [22].

Cereal crops such as corn, barley, rice, wheat, grain sorghum, and oats, along with root tuber plants like cassava, carrots, potatoes, sweet potatoes, radishes, yams, cactus, onions, and arrowroot, are rich in starch content [23]. In the United States, approximately 95% of bioethanol production is derived from corn biomass, with the remaining 5% produced from barley, wheat, whey, and other residues [24]. Sweet sorghum, another raw material source for bioethanol production, has been garnering significant attention in the U.S. Meanwhile, in Thailand, the economic viability of bioethanol production from cassava is under investigation. Cassava tubers contain about 80% starch by mass and less than 1.5% protein by mass. The pretreatment process for cassava tubers in bioethanol production involves cleaning, peeling, pulverizing, and drying. The dried cassava chips are then used for bioethanol production [25].

To produce bioethanol from starch-containing feedstock sources, the starch must be hydrolyzed into glucose syrup, primarily using enzymes such as α-amylase and glucoamylase. This glucose syrup can then be fermented into ethanol by the yeast *Saccharomyces cerevisiae*. This hydrolysis step incurs additional costs compared to bioethanol production from sugar-containing feedstocks. The α-amylase enzyme is produced by bacteria such as *Bacillus licheniformis*, and genetically modified strains of *Escherichia coli* and *Bacillus subtilis*. In contrast, molds like *Aspergillus niger* and Rhizopus species produce glucoamylases [26].

Under anaerobic conditions, *S. cerevisiae* ferments only glucose monomers to ethanol, achieving a maximum conversion efficiency of approximately 51% by mass. However, this yeast also uses glucose monomers for the synthesis of other metabolic products and cell growth, reducing the overall conversion efficiency [27]. As a result, *S. cerevisiae* typically converts about 40–48% of the glucose monomers by mass into ethanol.

2.2 Oil crops

2.2.1 Jatropha oil

Jatropha curcas, a member of the *Euphorbiaceae family*, represents a second-generation biomass source with potential for biodiesel production, distinctively not competing with food purposes. Thriving in tropical and subtropical environments, this plant typically grows 3–10 meters tall and varies in oil content across regions, containing approximately 12–47% oleic acid, 28–47% linoleic acid, around 14% palmitic acid, and 1–17% stearic acid. The *Jatropha* plant's high saturation levels of both saturated and unsaturated fatty acids make it particularly suitable for biodiesel production due to its semi-drying properties [28]. Current data suggests that *Jatropha curcas* can yield up to 2000 liters of biodiesel per hectare annually [29].

2.2.2 Karanja oil

The *Pongamia pinnata* plant, commonly known as Karanja, is an underutilized tropical species, particularly prevalent in India where it often serves as a roadside canopy. This medium-sized plant matures within 4–5 years. The seeds of Karanja contain approximately 27–40% oil, yielding between 10 and 30 kg per tree. On a hectare basis, it is estimated that about 1.8095 tons of oil can be produced, translating to roughly 1.62855 tons of biodiesel [30]. Utilizing this valuable biomass resource holds the potential for converting it into a viable energy source.

Karanja oil offers advantages over *Jatropha* oil, emitting fewer harmful substances and being relatively cost-effective [31]. Studies have demonstrated that the kinematic viscosity and specific gravity of Karanja oil decrease after the biodiesel production process. Furthermore, biodiesel derived from Karanja oil and its blends exhibit a higher flash point and density compared to conventional diesel fuel, indicating comparable performance to diesel fuel [32].

2.2.3 Hemp oil

The hemp plant, an annual species, can rapidly grow up to 5 meters tall within just 3–4 months, making it advantageous for quick harvesting compared to many other crops. Cultivated for various purposes for over 4500 years, hemp has been selectively bred into numerous varieties tailored for fiber, medicinal, and oil production. Hemp seeds are particularly valuable due to their high oil content, typically ranging from 26–38% [33], which makes hemp seed oil a viable food supplement rich in essential unsaturated fatty acids like omega-3 and omega-6 [34].

Hemp seed oil has a longstanding history as a fuel source, dating back centuries. Biodiesel production from hemp involves extracting fats and oils through seed pressing, followed by transesterification to produce biodiesel. Hemp biodiesel meets ATSM, D6751, and EN 14214 standards and exhibits superior performance compared to conventional diesel. It is estimated that hemp seed oil could yield over 800 liters per hectare annually, surpassing other crops like sunflower, soybean, peanut, or rapeseed [35]. Studies indicate that blending hemp biodiesel with petroleum diesel enhances cold flow properties, kinematic viscosity, and density [36].

2.2.4 Castor oil

The castor oil plant, a native of North Africa and Eurasia, has a rich history dating back to 4000 BC and has been utilized across various sectors globally. In recent years, castor oil has garnered attention for biodiesel production. India and China notably produce approximately 2 million tons annually of this plant [37]. Castor oil seeds boast an oil content of about 55%, which is significantly high compared to other plant seeds, positioning castor oil as a promising biodiesel feedstock. Its high viscosity can be mitigated by blending castor oil biodiesel with petroleum-based biodiesel to achieve optimal performance [38]. Despite limited research on biodiesel production from castor oil, studies indicate a yield of 431.7 kg/ha [39]. The potential of castor oil, especially when blended with diesel oil, shows promising prospects.

2.2.5 Rubber seed oil

The rubber tree, native to Africa and widely cultivated in Thailand, Indonesia, and India, produces seeds that are inedible but rich in oil content, ranging from 45–60%. The oil from rubber seeds consists of approximately 19% saturated fatty acids and 81% unsaturated fatty acids, enhancing stability and cetane number in biodiesel production. This nonedible seed oil does not compete with the food industry, making it a viable source of biodiesel. Research by Ref. [40] explored biodiesel production from a blend of rubber seed oil and palm oil, confirming its compliance with international standards. Studies suggest that 1000 tons of rubber seeds yield approximately 160 kilograms of biodiesel [41], highlighting the potential contribution of rubber seed oil to biodiesel production.

2.2.6 Soybean oil

Soybean seeds are commonly utilized for producing both cooking oil and biodiesel, containing approximately 20% lipids by weight [42]. Soybean oil comprises several fatty acids, including stearic acid, oleic acid, palmitic acid, linoleic acid, and linolenic acid. Compared to petroleum biodiesel, soybean biodiesel meets standard acid number limits, ensuring minimal issues such as corrosion and pump clogging due to low free fatty acid content [43]. Environmental benefits of soybean biodiesel over petroleum diesel are evident, attributed to its composition of fatty acids that improve viscosity and cetane number, thereby enhancing engine performance [44]. Soybean oil has been shown to yield approximately 598.6 liters of biodiesel per hectare, yet its sustainability as a first-generation feedstock source is debated in biodiesel production [45].

2.2.7 Palm oil

The palm oil plant is renowned for its high oil yield of approximately 5 tons per hectare annually. Biodiesel studies focus on palm oil due to its abundant production from palm fruit, notably in countries like Indonesia and Malaysia, where yields are about ten times higher than those from soybean, sunflower, and rapeseed crops [46]. Despite requiring minimal fertilizer and water, palm plants are renewable and sustainable, offering advantages such as a high cetane number, low sulfur content, and a high flash point in biodiesel production. However, its high viscosity poses challenges such as ignition delay and performance difficulties in cold weather conditions [47]. Ongoing efforts aim to mitigate these drawbacks. It is reported that palm plants yield approximately 5950 liters of biodiesel per hectare [48].

2.2.8 Canola oil

The canola plant, also known as rapeseed, is abundant in North America and considered one of the crucial oilseed crops globally. With its seeds containing approximately 45% oil, it has become a focal point in biodiesel production [49]. Canola oil, possessing a higher oil content compared to sunflower and palm oils, is favored in biodiesel production due to its excellent oxidation stability. Its composition of high fatty acids and low melting point makes it suitable as an alternative to petroleum diesel without necessitating engine modifications. Research indicates that blending crude oil with canola oil biodiesel maintains favorable density and viscosity levels for vehicle use [50]. With canola plants yielding 519 liters of biodiesel per hectare, it underscores their potential in sustainable biofuel production [51].

2.2.9 Cottonseed oil

Cotton (*Gossypium hirsutum L.*) holds significant global importance, predominantly in the textile industry. Cottonseed oil, derived from seeds left over after cotton fiber extraction, contains up to 24% oil content. Regarding protein content, cotton ranks second only to soybeans [52]. The composition of saturated and unsaturated fatty acids in cotton plants makes them a viable option for biodiesel production. Moreover, its short 3-month harvest cycle enhances its appeal as a biodiesel raw material. Turkey produces approximately 1.5 million tons of cottonseed annually. However, due to lower oil content compared to other sources, cottonseed yields about 230 kg of biodiesel per hectare [53].

2.2.10 Yellow grease

The affordability of raw materials is a critical factor in biodiesel production. Two primary types of greases are distinguished: yellow grease, with free fatty acids typically below 20% by weight, and brown greases, where free fatty acids exceed 20% by weight [54]. Research indicates that restaurants and fast-food establishments in the USA generate approximately 1.1 billion kg of waste oil annually [55]. Yellow grease, due to its high free oil content and challenges in saponification, is often deemed unsuitable for biodiesel production. While cheaper than fresh vegetable oils like soybean oil, its availability is limited as these oils are also used in animal feed or soap production, in addition to fuel production. In the U.S., an estimated 344 million gallons of biodiesel are produced annually from around 2.633 billion pounds of yellow grease [56].

2.2.11 Cooking oil

Waste cooking oil results from repeated frying of edible vegetable oils. Typically, this waste is disposed of in landfills or areas such as seas and rivers, contributing to environmental pollution. In the United States, approximately 10 million tons of waste cooking oil are generated annually, whereas China produces about 4.5 million tons [57]. The repeated frying process alters the physical and chemical properties of the oil, leading to substance transfer and oxidation reactions with the food it contacts. Research indicates that waste cooking oil tends to have high viscosity, a high flash point, and elevated free fatty acid content, all of which can significantly impact biodiesel yield [58]. These characteristics can be mitigated through the evaluation and treatment of waste oils, making them suitable for biodiesel production. It has been reported that 1 liter of biodiesel requires approximately 1.009 liters of waste cooking oil [59], highlighting the potential of these high-yield waste oils for producing environmentally friendly and sustainable biodiesel.

2.2.12 Tallow oil

Tallow, an animal fat sourced from cattle remains such as bones and internal organs, is a biodiesel raw material that offers significant environmental and economic advantages. Typically used in large quantities for soap production, animal fats like tallow can also be utilized in biodiesel and other chemical industries. Due to soap production being less than tallow supply, surplus tallow is often either incinerated or deposited in landfills, contributing to environmental pollution. Therefore, producing biodiesel from leftover tallow serves as an effective alternative to fossil fuels, ensuring efficient resource utilization. Tallow is cost-effective compared to vegetable oils. Bovine tallow diesel shares the same density as petroleum diesel but exhibits higher viscosity and flash point. Studies demonstrate that blending bovine tallow biodiesel with diesel maintains or enhances fuel properties compared to diesel alone [60]. The production yield of biodiesel from bovine tallow is reported to be 0.74 liters from one liter of beef tallow [61].

2.2.13 Pork fat

In many countries, waste lard is produced after cooking pork. Converting this waste lard into biodiesel offers both environmental and economic advantages by reducing its environmental impact. Due to its higher viscosity compared to petroleum diesel, lard biodiesel is not directly suitable for use in diesel engines. Research indicates that in industrial settings, 100 kg of oil and 10 kg of alcohol react with an alkaline catalyst to produce 100 kg of biodiesel and 10 kg of glycerin [62].

2.3 Lignocellulosic crops

The utilization of lignocellulosic biomass is complicated due to physical barriers created by lignin, which obstruct hydrolytic enzymes from accessing the cellulosic component [63]. Consequently, the process of converting lignocellulosic biomass into biodiesel involves several distinct unit operations: Pretreatment/depolymerization, hydrolysis/saccharification, cultivation of microorganisms for lipid production, and *trans*-esterification.

2.3.1 Structural features of lignocellulosic

The main components of lignocellulosic biomass are cellulose, hemicellulose, and lignin, comprising approximately 30–35%, 20–25%, and 15–20% respectively by dry weight [64, 65]. The arrangement of lignocellulosic varies depending on factors such as age, growth conditions, and geographical location [66]. Kumar et al. provided a comprehensive list of lignocellulosic biomass types along with their cellulose, hemicellulose, and lignin compositions by dry weight (%) [67].

The production of biodiesel from lignocellulosic biomass involves four main steps: delignification, enzymatic hydrolysis, fermentation with microbes to enhance lipid synthesis, and subsequent transesterification [68, 69].

Lignin, a polymer composed of phenylpropanoid units, is a non-carbohydrate fraction present in the primary cell wall [70, 71]. It consists of sinapyl alcohol, coumaryl alcohol, and coniferyl alcohol units linked by various ether bonds, providing resistance against microbial attack, impermeability, and tensile strength. Lignin acts as a barrier against microbial and saccharification processes due to its close association with cellulose microfibrils [72]. Lignin composition varies among different raw materials and must be reduced through delignification processes to facilitate access to hemicellulose and cellulose polymers [73].

Cellulose, occupying a significant portion of the plant cell structure, is a polymer of D-glucose moieties linked by β-1,4-glycosidic bonds with a degree of polymerization of 10,000 or higher. Cellulose polymers are packed into microfibrils through hydrogen bonds and Van der Waals forces, contributing to tensile strength, resistance against microbial degradation, crystallinity, and chemical stability [74, 75]. Cellulose exhibits inherent properties that confer resistance to lignocellulosic biomass [70].

Hemicellulose comprises various monomer units such as D-xylose, D-galactose, D-glucose, D-mannose, L-arabinose, 4-O-methyl-D-glucuronic acid, and D-glucuronic acid. Its structure is not well defined with a degree of polymerization typically below 200 [76]. After cellulose, hemicellulose is the second most abundant polymer, with its composition varying depending on the raw material. For instance, softwoods contain glucomannan, whereas grasses and agricultural residues (such as straw) contain xylan [77]. Hemicelluloses bind to cellulose and lignin microfibrils, imparting sensitivity and mechanical strength to chemical and thermal processes [70].

Effective hydrolysis requires the removal of at least 50% of hemicellulose to enhance cellulose digestibility. However, purification parameters must be carefully optimized to minimize furfurals and HMFs that hinder the fermentation process. Pretreatment conditions are often adjusted to maximize sugar recovery, with hemicellulose being obtained as either liquid or solid fractions depending on the process [74].

2.3.2 Miscanthus

Currently, Miscanthus is planted on approximately 30,000 hectares of land in Europe, according to the OPTIMISC FP7 Project. *Miscanthus sinensis* genotypes exhibit robust tolerance to diverse climates. A ten-year Miscanthus trial conducted by the University of Illinois from 2003 to 2013 reported an average annual yield of 10.5 tons per acre, which is twice that of Switchgrass plantations. The trial demonstrated that Miscanthus thrives with minimal or no fertilizer. Over five years, rhizomes and roots contribute approximately 12 tons of dry biomass per acre. Miscanthus' extensive root system makes it suitable for erosion control on slopes and soil stabilization [78]. In March 2012, Mendel Biotechnology (Mendel Bioenergy Seeds) announced a 4-year field experiment of PowerCane™ Miscanthus in collaboration with BP biofuels, aiming to explore its potential as a feedstock for their cellulosic ethanol demonstration plant in Jennings.

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2.3.3 Giant king grass, elephant grass and Napier grass

Pennisetum purpureum, a member of the Poaceae family, is a perennial tropical grass native to Africa, primarily used as a forage plant. It is notable as an energy crop due to its potential to yield up to 40 tons per hectare annually and can be harvested 4–6 times a year. Moreover, it requires minimal nutrients and water. In California, Viaspace Inc. is spearheading projects involving Giant King Grass for advanced biomethane and biofuel production.

2.4 Manures and organic wastes

Agricultural wastes encompass materials resulting from various agricultural activities and processes that are no longer useful and categorized as waste [79, 80]. These wastes include crop residues, industrial processing residues, livestock wastes, and fruit wastes [81, 82]. Improper management of agricultural waste can pose environmental hazards, pollute terrestrial and aquatic habitats, and impact human health adversely. Therefore, effective waste management strategies such as reuse, recycling, and reduction are essential.

Transforming agricultural waste into valuable forms represents a highly sustainable, environmentally friendly, and economical approach to waste management. This not only contributes to socioeconomic development, environmental cleanliness, resource recovery, and conservation but also promotes circular economy principles and enhances energy security [83].

Numerous studies have explored various methods for converting and recycling agricultural waste. For instance, Ref. [84] conducted comprehensive research on biofuel production from citrus fruits, while Ref. [85] focused on biofuel production from waste cooking oil. Recent studies have demonstrated the feasibility and applicability of diverse conversion processes, achieving conversion efficiencies ranging from 70–95% in many cases [86, 87]. Additionally, utilized carbonization and hydrothermal processes to convert food waste into biofuel [88], and employed pyrolysis and other methods to transform waste plastics into biofuels [89].

Microorganisms such as *Clostridium acetobutylicum*, *Clostridium difficile*, *Pseudomonas* sp. CL3, *Clostridium* sp. TCW1, and *Ruminococcus* play pivotal roles in biodegrading agricultural wastes into biofuels and other valuable products in an environmentally friendly manner, albeit at a relatively slow pace [90]. Agricultural residues like rice straw, corn cobs, oil cakes, sugarcane bagasse [91], banana peels [92], wheat straw, sawdust, and rice husks [93] have been successfully converted into biogas, bio-oil, biobutanol, bioethanol, biodiesel, organic acids, enzymes, and other beneficial products.

The increasing global population, socio-cultural trends, industrialization, and economic activities have significantly escalated energy demands. For example, the world population, which was approximately 7.3 billion in 2018, is projected to reach 9.735 billion by 2050. Correspondingly, total energy consumption has risen from 543 EJ in 2015 to 575 EJ in 2018 and is anticipated to reach 725 EJ by 2030 [94]. However, this increased energy consumption contributes to higher global CO_2 emissions from fossil fuel combustion.

Furthermore, global waste production was 2.02 billion tonnes in 2016 and is expected to rise to 3.4 billion tonnes by 2050 [95]. The world waste management market, valued at 1.61 trillion US dollars in 2020, is projected to reach 2.5 trillion US dollars by 2030, with East Asia and the Pacific region expected to generate the largest amount of waste [94].

2.5 Wood products

Wood refers to a solid lignocellulosic material naturally produced in trees and some shrubs, comprising approximately 40–50% cellulose, 20–30% hemicellulose, and 20–30% lignin. Two primary options for solid biomass energy are wood and grass, both used in biodiesel production. Variations in feedstocks lead to differences in fuel composition, properties, and performance, aspects that have not been fully explored include their susceptibility to knocking.

Energy production and forest-based industries are closely interconnected, exhibiting both competition and synergy [96]. Byproducts from chemical pulp are utilized in energy and chemical industries, whereas sawmill byproducts contribute to wood pulp for textiles and paper, as well as the manufacture of wood-based panels and energy production. The supply of primary woody biomass, particularly for electricity generation, is heavily influenced by timber demand and natural disruptions affecting biomass availability. Harvesting wood biomass competes for material and energy use, prioritizing wood-based panels and wood pulp over saw logs due to higher costs [97].

Economic evaluations increasingly guide forestry investment decisions, ensuring the selection of optimal projects and potential production alternatives. Economic assessments of wood productivity extend from harvesting to field stacking [73].

Forests yield biomass through harvesting, with additional biomass obtained during silvicultural processes such as thinning and pruning. These practices involve removing parts or entire sections of forests for energy, timber, or other products and services, impacting biodiversity by removing shrubs that serve as habitats [98].

2.6 Algae and aquatic biomass

2.6.1 Microalgae

Microalgae, the raw material for third-generation biofuels, are among the oldest microorganisms on earth, existing as prokaryotic or eukaryotic organisms with rapid growth rates due to their unicellular or multicellular structures. They grow approximately 100 times faster than traditional plants [99]. Certain microalgae species accumulate lipids within their cells, which can be converted into biodiesel. These lipid-producing microalgae are highly regarded for their noncompetition with food crops, fast growth, minimal water requirements, CO_2 tolerance, low production costs, and versatile applications across various sectors [100]. Freshwater microalgae like *Chlorella emersonii* and *Botryococcus sp.* can yield between 60 and 75% lipids on average, while seawater microalgae such as *Dunaliella tertiolekta*, *Dunaliella sp.*, and *Neochloris oleoabundans* can accumulate around 65–70% lipids [101]. Microalgae cells differ from plant cells, and laboratory studies on lipid extraction typically use chloroform and methanol solutions. Research indicates that 71 grams of biodiesel can be produced from 1 kilogram of microalgae biomass [102]. Despite their high potential for biodiesel production, limited engine testing and emissions studies with microalgae biodiesel have shown promising performance.

Aquatic plants share many characteristics with terrestrial plants, albeit with lower lignin content, requiring simpler pretreatment processes. They are rich in sugars, starches, oils, and proteins, making them promising feedstocks for biorefineries [103]. They also exhibit high photosynthetic efficiency, robust biomass production, and rapid growth rates. With proper management, surplus aquatic biomass can be utilized in biorefineries to produce various bioproducts such as fish meal, soil compost, protein sources, biofuels, biofertilizers, and value-added products.

Despite these advantages, the utilization of aquatic plants in bioproduct production within biorefineries remains limited. Some reviews have focused on biofuel production from various aquatic plants, while others have explored the potential of specific aquatic plant species for biofuel production [104]. Different harvesting and pretreatment techniques precede biofuel production. Research on biodiesel production from aquatic plants has primarily focused on species like Lemna sp., Azolla, water lettuce, and water hyacinth, although their lipid contents are relatively lower compared to microalgae and require further investigation [105]. Duckweed, for example, contains significant fatty acids such as palmitic acid, linolenic acid, *p*-coumaric acid, and linoleic acid, which can also be utilized for biodiesel production [106]. Despite their potential as biofuel feedstocks, the applicability of aquatic plants for biodiesel production is still in its early stages and warrants extensive research efforts.

Aquatic plants thrive in both tropical and temperate climates and can be free-floating, submerged, or emergent (rooted), adapting easily to various environmental conditions, including saline and polluted waters [107]. They require minimal maintenance, exhibit high adaptability, and can produce substantial biomass under favorable conditions. With increasing nutrient inputs into water bodies from waste, aquatic plants are thriving and utilizing these resources efficiently. Plant biomass comprises complex compounds such as proteins, lipids, and carbohydrates [108]. Globally, the harvest of aquatic plants reached 10.5 million tonnes in 2000 and is projected to increase to 34 million tonnes by 2018 and further by 20% in 2030 [109].

3. Conclusions

The objective of this chapter is to offer a contemporary analysis of technologies aimed at converting agricultural waste into advanced biofuels. This review focuses on the utilization of agricultural wastes as primary materials for producing biodiesel, biomethanol, bioethanol, biobutanol, and biohydrogen. By compiling current advancements in techniques for converting waste from diverse agricultural activities into biofuels, this chapter aims to stimulate further research in this field. At the same time, this chapter aims to provide accessible information to researchers, biofuel producers, farmers, policymakers, environmental advocates, investors, governments at various levels, and other stakeholders by addressing the global demand for renewable fuels obtained from agricultural waste.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

Biodiesel Technologies: Recent Advances, New Perspectives, and Applications

Carine Tondo Alves, Luciano Sergio Hocevar and Lilian Lefol Nani Guarieiro

Abstract

This chapter explores the latest advancements in biodiesel technologies, highlighting innovative approaches and emerging perspectives shaping the future of sustainable energy. It explores cutting-edge methods in biodiesel production, including novel catalysts, feedstock diversification, and process optimization. The chapter also examines these technologies' environmental and economic impacts, emphasizing their potential to reduce greenhouse gas emissions and dependence on fossil fuels. Additionally, it discusses the integration of biodiesel with other renewable energy sources and its applications in various sectors, such as transportation and industry. By providing a comprehensive overview of recent developments and future trends, this chapter aims to offer valuable insights for researchers, policymakers, and industry stakeholders committed to advancing the biodiesel industry.

Keywords: biodiesel, new perspectives, energy, renewable energy, biofuels

1. Introduction

Since the 1700s, fossil fuels have been the backbone of global energy production, driving industrialization, transportation, and economic growth worldwide [1, 2]. However, by the late 2000s, the adverse environmental impacts of fossil fuel dependency became increasingly evident, particularly its role in escalating greenhouse gas emissions and climate change. These developments have profound implications for both human and animal life, prompting many nations to aim for net-zero carbon emissions and accelerate the shift to renewable energy sources. Renewable energy, with its potential to reduce greenhouse gas emissions and mitigate climate change, has since gained significant attention as a more sustainable and cleaner alternative [3, 4].

Biodiesel production primarily relies on the chemical process of transesterification, where triglycerides from oils and fats react with an alcohol, typically methanol or ethanol, in the presence of a catalyst. This reaction produces fatty acid methyl esters (FAME), which constitute biodiesel, and glycerol as a by-product. The choice of feedstock, catalyst, and production method significantly influences the quality, yield, and economic feasibility of biodiesel production [5].

Interest in biodiesel production and use surged globally between the 1980s and 2020s due to its status as a renewable energy source, its positive environmental and social implications, and its potential to replace fossil-based diesel, which is often imported. This makes biodiesel economically and geopolitically significant. Additionally, biodiesel can be produced from a wide range of feedstocks, including vegetable oils, animal fats, and waste materials such as used cooking oil. These characteristics have positioned biodiesel as a key component in the energy and economic planning of several countries [6].

Among the various renewable energy options, biodiesel has emerged as a promising substitute for fossil fuels, particularly petroleum diesel. Biodiesel is produced through the transesterification of animal fats and vegetable oils using alcohols like methanol or ethanol. This process converts triglycerides into fatty acid methyl esters (FAME), reducing the molecular weight and viscosity of the original oils while increasing their volatility. Notably, biodiesel also offers the potential to recycle carbon dioxide, contributing to a closed carbon cycle that further enhances its environmental benefits [7].

The evolution of biodiesel production has progressed through several generations, each characterized by the type of feedstock used. The first generation of biodiesel primarily relied on edible feedstocks such as soybean oil, palm oil, and coconut oil. These feedstocks were favored due to their availability and the relative simplicity of the conversion process. However, the use of edible oils raised concerns about food security and the sustainability of large-scale biodiesel production. The second generation of biodiesel focused on non-edible feedstocks like neem oil, rubber seed oil, and jatropha oil. The third generation of biodiesel, derived from microalgae and waste oils, offers even greater benefits [8].

Future research must focus on optimizing the thermophysical properties of biodiesel-diesel blends and refining the transesterification process to enhance biodiesel production efficiency and engine performance. As biodiesel technology continues to advance, it holds the potential to play a significant role in the global transition to cleaner, more sustainable energy sources. This chapter will discuss the latest advancements in biodiesel technologies, innovative approaches in production, environmental and economic impacts, and future trends in the industry.

2. Overview of biodiesel production

Biodiesel production has been a significant area of research over the past five years due to the increasing need for sustainable and renewable energy sources. The rise in population growth, industrialization, and welfare has led to an increased use of fossil fuels, resulting in higher greenhouse gas emissions and climate change. The negative impacts of these changes include increased floods, droughts, forest fires, and glacier melting, among other natural disasters. The Paris Climate Conference (2015), held during the Conference of the Parties (COP21), led to an agreement to limit global warming to below 2°C. Achieving this goal will require significant emission reductions to stabilize greenhouse gas concentrations in the atmosphere. Substituting fossil fuels with biofuels derived from plant biomass has the potential to drastically decrease greenhouse gas emissions. Biofuels, especially biodiesel, are receiving increasing research attention. The top five article-producing nations in this field are China, the United States, India, Australia, and France.

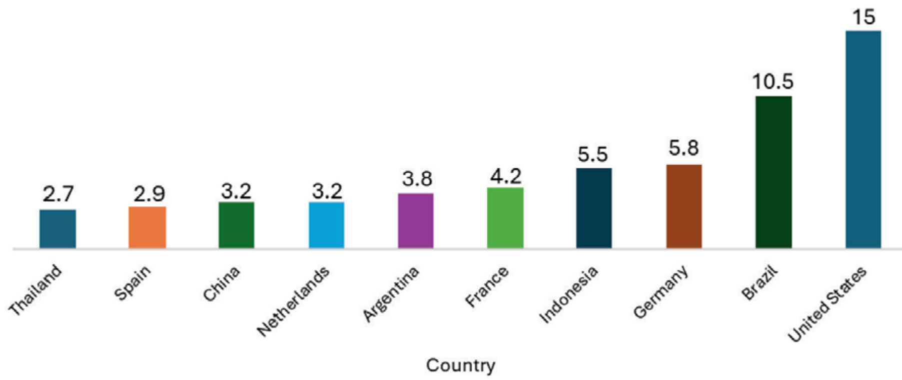

Figure 1.
Biodiesel world leading countries production in 2023.

According to data from the International Grain Council (IGC) reported by Germany's Union for the Promotion of Plants and Protein (UFOP), global biodiesel production has reached a record level. The increase in production was primarily fueled by increased soybean cultivation in the USA and South America, as indicated in the report dated June 6, 2024. The IGC estimates that global biodiesel production, including hydrotreated vegetable oil (HVO), reached a new peak of 71.5 million tons in 2023, an 11% increase from the previous year. This growth was mainly concentrated in North and South America, as well as Asia [9].

Global production for 2024 is projected to rise to 76.3 million tons, marking a 7% increase from the previous year's output. Over recent years, the USA, Brazil, and Indonesia have expanded their biodiesel production, collectively accounting for nearly 60% of the global output, up from 35% a decade earlier (**Figure 1**). In Brazil, substantial harvests are anticipated to meet domestic demand and exports, following

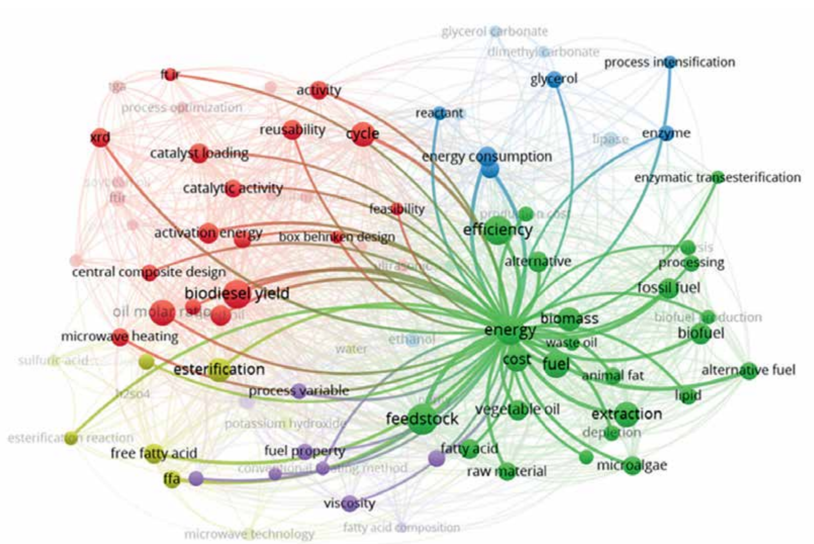

Figure 2.
Biodiesel production keywords. Font: Authors.

a 2% increase in the blending quota to B14 (14% biodiesel). This adjustment will boost domestic consumption of heavy goods vehicles (HGVs) [9].

Over the past five years, biodiesel production technologies have seen minimal technological breakthroughs, both at industrial and laboratory scales. However, existing processes are being refined and optimized to enhance economic viability, as illustrated in **Figure 2** made in VOSVIEWER software. Keywords such as energy efficiency, biomass, and biodiesel yield feature prominently in discussions about production advancements, reflecting the growing emphasis on these aspects. This trend aligns with the findings of recent bibliographic research and published studies in the field.

3. Biodiesel production technologies

This section delves into how the production of biodiesel has evolved significantly over the years, driven by advancements in technology and the need for more sustainable energy sources. This section delves into the traditional and emerging biodiesel production methods, the chemical processes involved, the role of various catalysts, recent technological innovations, and the diversification of feedstocks. Additionally, it covers a techno-economic analysis, comparing the costs and scalability of different production technologies.

3.1 Traditional biodiesel production methods

Biodiesel production traditionally centers around the process of transesterification, a chemical reaction that converts triglycerides, found in oils and fats, into fatty acid methyl esters (FAME) and glycerol. This method has been the backbone of biodiesel production due to its simplicity and effectiveness in transforming a wide range of feedstocks into usable fuel. The transesterification process involves reacting triglycerides with an alcohol (usually methanol or ethanol) in the presence of a catalyst. The choice of catalyst—whether acid, base, or enzyme—significantly influences the reaction efficiency, yield, and quality of the biodiesel produced.

3.1.1 Transesterification process

Transesterification is the primary chemical process used in biodiesel production, where triglycerides from oils or fats react with alcohol to produce FAME and glycerol [10]. **Figure 3** illustrates the base-catalyzed mechanism for triglycerides using alkali hydroxide as a catalyst. In the first step (1), the catalyst reacts with alcohol to produce an alkoxide. This alkoxide then performs a nucleophilic attack on the carbonyl group of the triglyceride, forming a tetrahedral intermediate (2). From this intermediate, an alkyl ester and the corresponding anion of the triglyceride (3) are generated. Finally, the catalyst is deionized, regenerating the active compound (4), which can then react with another alcohol molecule, initiating a new catalytic cycle. In this notation, B represents the base catalyst, R1, R2, and R3 denote the carbonyl groups of fatty acids, and R signifies the functional group of the alcohol [10].

This reaction is typically catalyzed by acids, bases, or enzymes, depending on the feedstock and desired outcomes [10].

Acid catalysis: Acid catalysts, such as sulfuric acid, are effective in transesterifying oils with high free fatty acid (FFA) content. While acid catalysis is less sensitive to FFA content, it requires longer reaction times and higher alcohol-to-oil ratios, making it less efficient for large-scale production.

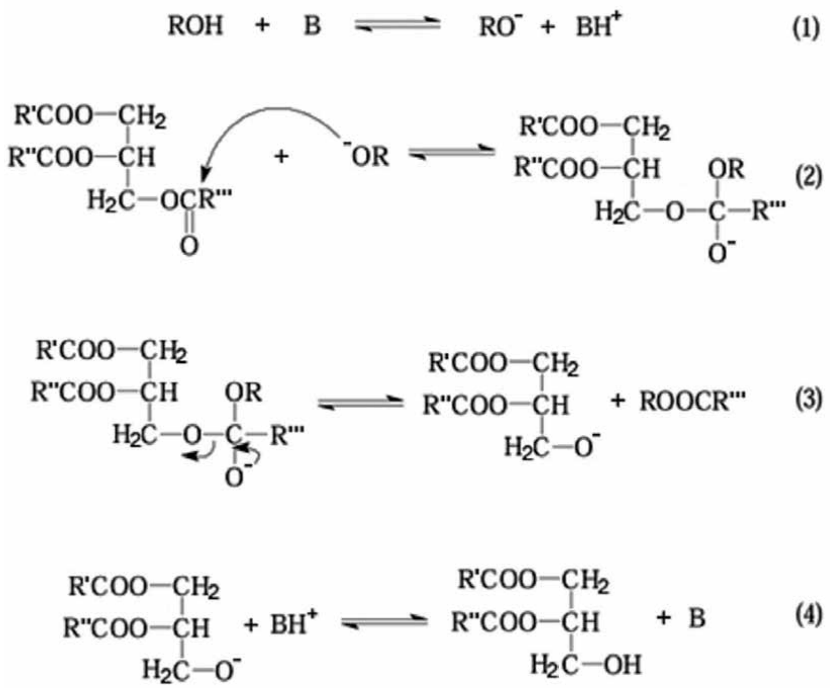

Figure 3.
Transesterification reaction mechanism [9].

Base catalysis: Base catalysts, like sodium hydroxide (NaOH) or potassium hydroxide (KOH), are the most used in biodiesel production. They are highly effective with low FFA oils, offering faster reaction rates and higher yields. However, base catalysis is sensitive to the presence of water and FFAs, which can lead to soap formation and lower biodiesel yield.

Enzyme catalysis: Enzymatic transesterification, using lipase enzymes as catalysts, offers a more environmentally friendly alternative. This method works well with a variety of feedstocks and operates under milder conditions without the need for alcohol recovery. However, the high cost of enzymes and slower reaction rates are barriers to widespread commercial adoption.

3.1.2 Recent technological advances

To address the limitations of traditional transesterification, recent technological advancements have focused on improving reaction efficiency, reducing costs, and enabling the use of lower-quality feedstocks.

Supercritical fluid technology: Supercritical fluid transesterification is a cutting-edge method that eliminates the need for a catalyst. In this process, alcohol is used in its supercritical state—where it exhibits properties of both liquids and gases—at high temperatures and pressures. This technology offers several advantages, including faster reaction times, higher yields, and the ability to process feedstocks with high FFA content. However, the high energy requirements and associated costs are significant challenges for large-scale implementation [11].

Microwave-assisted transesterification: Microwave-assisted transesterification leverages microwave radiation to enhance the reaction kinetics by providing uniform and rapid heating. This technology reduces reaction time and energy consumption compared to conventional heating methods. It also improves the overall yield of biodiesel, making it a promising innovation for industrial-scale production. The scalability and integration of microwave technology into existing production facilities are areas of ongoing research [12].

Ultrasonic-assisted transesterification: Ultrasonic-assisted transesterification utilizes ultrasonic waves to induce cavitation—forming and collapsing microbubbles within the reaction mixture. This cavitation accelerates the mixing of reactants, enhancing mass transfer and reaction rates. The process is particularly effective for high-viscosity feedstocks and significantly reduces reaction times. However, challenges remain in scaling up ultrasonic systems for large-scale biodiesel production [13, 14].

3.1.3 Feedstock diversification

The sustainability and economic viability of biodiesel production are heavily influenced by the choice of feedstocks. Traditionally, biodiesel production has relied on edible oils, but there is a growing shift toward using non-edible and waste oils, as well as algae, to reduce costs and environmental impact.

Edible oils: Common edible oils used in biodiesel production include soybean oil, palm oil, and rapeseed oil. These oils are readily available and have well-established supply chains, making them popular feedstocks. However, using edible oils raises concerns about food security and the environmental impact of large-scale monoculture farming.

Non-edible oils: Non-edible oils, such as jatropha, neem, and karanja, offer a more sustainable alternative to edible oils. These oils are often derived from plants that can grow on marginal lands, reducing competition with food crops. Additionally, non-edible oils typically have higher FFA content, which can be efficiently processed using acid or enzymatic catalysts.

Waste oils and fats: Waste oils and fats, such as used cooking oil, animal fats, and grease trap waste, are increasingly being used as feedstocks for biodiesel production. These waste materials are inexpensive and help address waste management challenges. Processing waste oils and fats into biodiesel not only reduces disposal costs and environmental impact but also contributes to the circular economy. The primary challenges with waste oils and fats are their variable quality and the need for pretreatment to remove impurities and reduce FFA content (**Figure 4**).

Algal biodiesel: Algae have emerged as a highly promising feedstock for biodiesel due to their high lipid content, rapid growth rates, and ability to grow in a variety of environments, including wastewater and non-arable land. Algal biodiesel production has the potential to overcome many limitations associated with traditional feedstocks, such as land use and water requirements. However, the high costs associated with algal cultivation, harvesting, and oil extraction remain significant barriers to commercialization.

3.1.4 Techno-economic analysis

The economic viability of biodiesel production is a critical factor in its adoption and scalability (**Figure 5**). A comprehensive techno-economic analysis involves comparing the costs associated with different feedstocks and production technologies, as well as assessing their scalability for industrial adoption [15].

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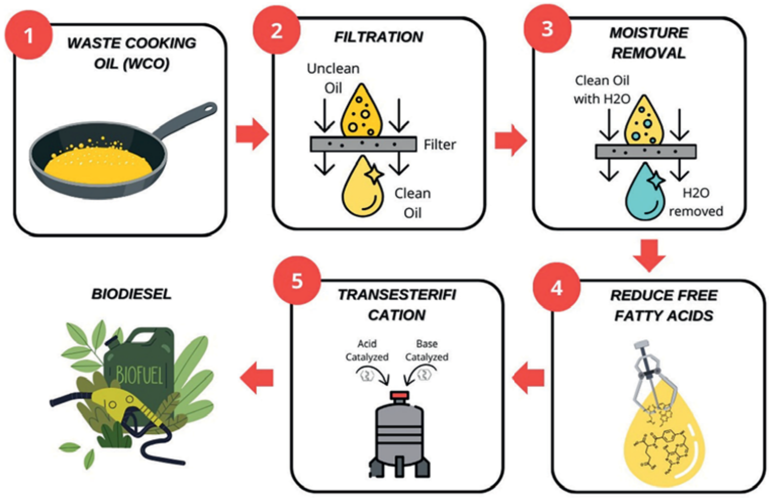

Figure 4.
Transesterification process using waste cooking oils to produce biodiesel. Font: Authors.

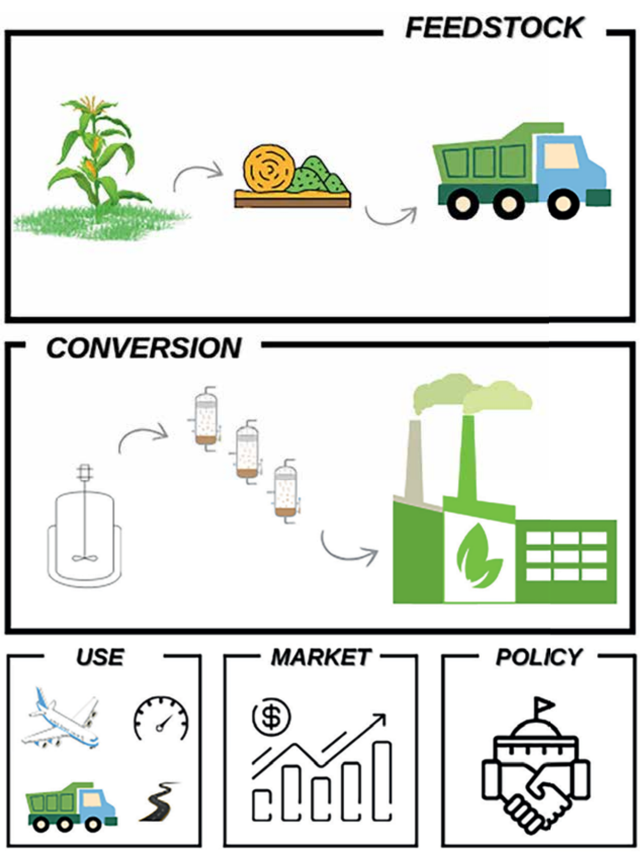

Figure 5.
The economic viability of biodiesel production. Font: Authors.

Feedstock costs: The cost of feedstock is the most significant factor in the overall cost of biodiesel production. Edible oils tend to be more expensive due to their demand in the food industry, whereas non-edible oils and waste oils are generally cheaper but may require additional processing. Algal biodiesel, while promising, is currently the most expensive due to the high costs of cultivation and oil extraction [15].

Technology costs: The choice of production technology also impacts the cost structure. Traditional base-catalyzed transesterification is the most cost-effective method but is limited by the quality of the feedstock. Advanced technologies, such as supercritical fluid transesterification and microwave-assisted transesterification, offer higher yields and the ability to process lower-quality feedstocks but come with higher capital and operational costs [15].

3.1.5 Scalability and industrial adoption

The scalability of biodiesel production technologies is essential for meeting global energy demands. Traditional transesterification processes are well-established and can be scaled up relatively easily. However, the adoption of advanced technologies requires significant investment in infrastructure and a thorough understanding of the techno-economic trade-offs. The integration of these technologies into existing industrial processes, along with supportive policies and market conditions, will determine the future role of biodiesel in the global energy landscape [15]. Biodiesel production technologies are evolving rapidly, driven by the need for more sustainable and economically viable energy sources. The continued development of advanced production methods, feedstock diversification, and comprehensive techno-economic analyses will be crucial in overcoming the challenges facing the biodiesel industry and ensuring its long-term success.

3.2 Environmental and economic perspectives

3.2.1 Life-cycle analysis (LCA) of biodiesel: Environmental benefits, greenhouse gas emissions, and carbon footprint reduction

Life-cycle analysis (LCA) (**Figure 6**) is an essential tool for assessing the environmental impact of a product or process throughout its entire life cycle. For biodiesel, LCA provides a comprehensive evaluation of its sustainability by analyzing the energy and material inputs, outputs, and environmental consequences from feedstock cultivation to fuel combustion. A well-conducted LCA captures the environmental benefits of biodiesel, particularly in terms of its potential to reduce greenhouse gas (GHG) emissions and its overall carbon footprint, when compared to conventional fossil fuels [16]. The LCA of biodiesel typically involves four stages: (1) feedstock production, (2) transportation and processing of feedstock, (3) conversion of feedstock to biodiesel, and (4) use of biodiesel as fuel, including combustion and emissions. The analysis must consider the energy consumed and emissions produced at each stage, as well as the by-products and waste generated. To ensure comparability, the LCA for biodiesel is generally compared to the life cycle of petroleum diesel, the most widely used fossil fuel in transportation [16].

Energy return on investment (EROI): The ratio of energy produced in the form of biodiesel to the energy expended in producing it.

Greenhouse gas emissions: Typically measured in terms of CO_2-equivalent (CO_2e) emissions, these include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [17].

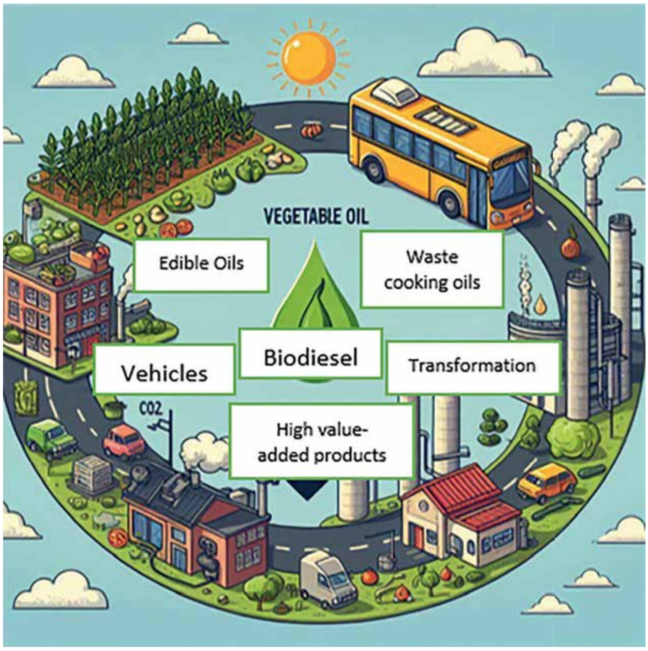

Figure 6.
LCA of biodiesel production. Font: Authors.

Carbon footprint: This includes both direct and indirect emissions associated with the production, transport, and combustion of biodiesel, expressed as a total mass of CO_2e emissions per unit of biodiesel produced [17].

One of the most compelling environmental benefits of biodiesel is its potential to significantly reduce GHG emissions compared to fossil fuels. The primary source of GHG emissions in fossil fuel life cycles comes from the extraction, refining, and combustion of petroleum, where carbon that has been stored underground for millions of years is released into the atmosphere as CO_2. In contrast, biodiesel is derived from recently living biological materials (biomass), such as vegetable oils, animal fats, and algae, which absorb CO_2 from the atmosphere during photosynthesis [16, 17].

A critical advantage of biodiesel is its partial carbon neutrality. Because the feedstocks used in biodiesel production (such as crops or algae) absorb CO_2 during their growth, biodiesel can offset some of the CO_2 released during its combustion. This concept of "biogenic carbon" is central to biodiesel's reduced carbon footprint:

Crop-based feedstocks: Biodiesel produced from crops like soybean or rapeseed involves CO_2 sequestration through plant growth. While the combustion of biodiesel releases CO_2, the CO_2 uptake during feedstock cultivation means that biodiesel's net CO_2 emissions are considerably lower than those of petroleum diesel [17].

Algae-based biodiesel: Algae cultivation presents an even more sustainable solution, as algae can sequester large amounts of CO_2 during photosynthesis. Algae-based biodiesel has the potential to be carbon-neutral or even carbon-negative if combined with CO_2 capture from industrial sources [17]. However, the degree of carbon neutrality depends on several factors, including the type of feedstock, cultivation practices, and land-use changes. The benefits can be diminished if biodiesel feedstock is produced using intensive agricultural methods or on land cleared from forests or other carbon sinks, a phenomenon known as indirect land-use change (ILUC) [17].

Multiple LCA studies have demonstrated that biodiesel consistently outperforms petroleum diesel in terms of GHG emissions reductions. On average, biodiesel can reduce lifecycle GHG emissions by 50–80% compared to fossil diesel, depending on the feedstock and production method [17].

Soybean-based biodiesel: One of the most studied feedstocks, soybean biodiesel, has been shown to reduce lifecycle GHG emissions by approximately 57% relative to petroleum diesel. Most of these savings arise from the biogenic CO_2 absorption during soybean growth, although energy inputs for fertilizer production, cultivation, and processing moderate the overall reduction [17].

Waste oil and grease biodiesel: Biodiesel produced from waste oils and greases, such as used cooking oil, offers even more substantial GHG reductions. Since waste oils are a by-product of other activities (e.g., cooking), their carbon footprint is low, and GHG savings can reach up to 86% compared to fossil diesel. This makes waste-derived biodiesel one of the most environmentally advantageous biofuels.

In addition to CO_2, biodiesel's life cycle also involves emissions of other potent GHGs such as methane (CH_4) and nitrous oxide (N_2O). For example, the production of fertilizers used in feedstock cultivation can result in significant N_2O emissions, which have a much higher global warming potential (GWP) than CO_2 [18]. However, compared to fossil fuels, the contribution of these non-CO_2 GHGs in biodiesel production is generally lower, especially when using sustainable farming practices. Advanced agricultural techniques, such as precision farming and integrated pest management, can further reduce these emissions, enhancing biodiesel's environmental benefits. Beyond GHG reductions, biodiesel production and use provide several other environmental benefits:

Lower sulfur and particulate emissions: Biodiesel contains no sulfur, and its use in diesel engines leads to significantly lower emissions of sulfur oxides (SO_x) and particulate matter (PM), which are major contributors to air pollution and acid rain [18–20].

Reduction of smog precursors: Biodiesel combustion results in lower emissions of nitrogen oxides (NO_2) and volatile organic compounds (VOCs), both of which contribute to ground-level ozone formation, a key component of smog [18–20].

Enhanced soil and water management: When biodiesel is produced from crops grown on marginal land or integrated into sustainable farming systems, it can support soil health and reduce water usage. Moreover, some feedstocks, such as algae, can be cultivated in wastewater, thereby recycling nutrients and reducing environmental contamination [18–20].

3.2.2 Economic feasibility and scalability

The economic feasibility and scalability of biodiesel production are critical factors that determine its potential to compete with fossil fuels and meet growing energy demands. Although biodiesel presents clear environmental benefits, its widespread adoption depends on overcoming economic barriers, including feedstock costs, production efficiency, and market infrastructure. Advances in technology, diversification of feedstocks, and supportive policies are essential to making biodiesel production both economically viable and scalable on a global level (**Figure 7**).

3.2.2.1 Feedstock costs and availability

Feedstock costs account for the largest portion of biodiesel production expenses, typically comprising 60–80% of total production costs. The economic viability of biodiesel depends heavily on the type and cost of feedstock used [21]:

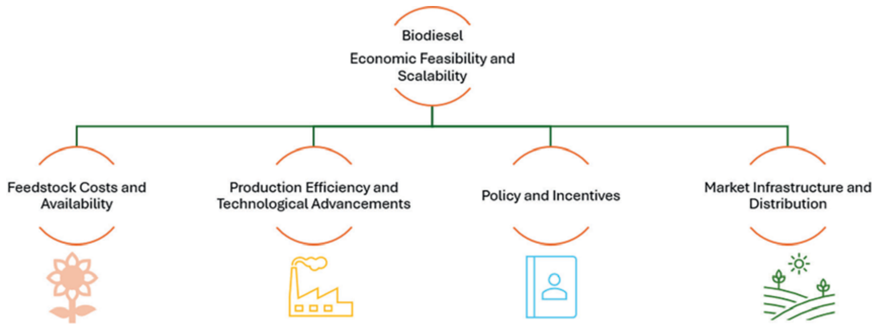

Figure 7.
Biodiesel economic feasibility and scalability. Font: Authors.

First-generation feedstocks: Traditional feedstocks, such as soybean oil, rapeseed oil, and palm oil, are well-established but relatively expensive due to competition with food markets. These costs limit the scalability of biodiesel from these sources, particularly in regions with high agricultural demand.

Waste oils and animal fats: Waste oils, such as used cooking oil and animal fats, offer a cost-effective alternative, as they are often cheaper and do not compete with food crops. Utilizing waste feedstocks can significantly lower production costs, making biodiesel more competitive. However, scalability is constrained by the availability of waste materials, which may not be sufficient to meet large-scale production needs [21].

Algae and non-traditional feedstocks: Algae and other third-generation feedstocks, which can be grown on non-arable land or in wastewater, offer significant potential for scalability. While still in the research and development phase, these feedstocks promise higher yields and lower land and water use, which could reduce production costs in the long run [21].

3.2.2.2 Production efficiency and technological advancements

Technological improvements in biodiesel production have a direct impact on economic feasibility. Innovations in catalysts, reactor design, and energy-efficient processes can reduce the overall costs of production:

Catalyst improvements: The shift from homogeneous to heterogeneous catalysts, as well as advancements in enzymatic catalysis, reduces the need for complex purification steps and lower energy consumption. These improvements enhance production efficiency, lowering operational costs [22].

Process intensification: Technologies such as continuous flow reactors and microreactors enable higher production rates with less energy input. These advances can make biodiesel production more economically scalable by reducing the footprint and infrastructure required for large-scale plants [22].

3.2.2.3 Policy and incentives

Government policies and incentives play a crucial role in the economic feasibility of biodiesel. Subsidies, tax credits, and mandates for renewable fuel standards (RFS) can help offset the higher costs of biodiesel production, making it more attractive to investors and producers [23]. In countries with strong biodiesel policies, such as the United States and European Union, the biodiesel market has grown significantly due to:

Blending mandates: Many governments require a certain percentage of biodiesel to be blended with petroleum diesel (e.g., B20, B100), creating a guaranteed market and ensuring demand [23].

Subsidies and tax credits: Direct financial support for biodiesel producers and tax incentives for consumers help make biodiesel more competitive with fossil fuels in the marketplace [23].

3.2.2.4 Market infrastructure and distribution

Scalability also depends on the development of infrastructure to support biodiesel production and distribution. Unlike petroleum diesel, biodiesel requires specialized storage and distribution systems due to its slightly different chemical properties (e.g., hygroscopicity). Investment in refining capacity, pipelines, and distribution networks is necessary to achieve large-scale production and widespread availability. As the biodiesel market expands, economies of scale can reduce costs, but initial investments are high [24].

4. Biodiesel blends and engine performance

Biodiesel is marketed in many countries, mixed with commercial diesel at varying percentages, each governed by specific national regulations defining the biodiesel content. As illustrated in **Table 1**, Brazil stands out as the country with the highest biodiesel percentage, and consequently, a diesel fuel with the highest renewable content. This prominence is attributed to Brazil's extensive territory and its significant potential for producing oilseed feedstocks. Among these feedstocks, soybean oil is particularly notable for its widespread use in biodiesel production [31–33].

In this context, biodiesel blends are a key factor in the transition from petroleum-based fuels to more sustainable alternatives. The impact of these blends on engine performance, fuel economy, and emissions varies depending on the concentration of biodiesel in the fuel. This section examines how different biodiesel blends influence engine behavior and highlights recent advances in engine technology that optimize performance with high-biodiesel blends.

Country	Biodiesel (B%)	Type of diesel (Sulfur)	Biodiesel feedstock	Ref.
Brazil	B13	S10 (less than 10 ppm)	Soybean, palm oil, animal fat	[25]
United States	B5	Ultra Low Sulfur Diesel (ULSD)	Soybean, corn oil	[26]
Germany	B7	Ultra Low Sulfur Diesel (ULSD)	Rapeseed (canola), soybean	[26]
Argentina	B10	S10 (less than 10 ppm)	Soybean, sunflower	[27]
France	B7	Ultra Low Sulfur Diesel (ULSD)	Rapeseed (canola)	[28]
India	B5	Ultra Low Sulfur Diesel (ULSD)	Castor oil, palm oil	[29]
China	B10	S10 (less than 10 ppm)	Soybean oil, rapeseed oil	[30]
Japan	B5	Ultra Low Sulfur Diesel (ULSD)	Soybean oil, canola oil	[30]

Table 1.
Type of diesel sold in different countries and the percentage of biodiesel present in diesel.

4.1 Biodiesel blends and emissions

In addition to biodiesel coming from a renewable source, its application in diesel cycle engines can bring other benefits, such as reducing the emission of some pollutants [34–36]. **Table 2** highlights some recent studies that observed a reduction in CO and Particulate Matter emissions, but an increase in NOx emissions. The higher the Biodiesel content added to diesel, the greater the NOx emissions due to the rise in temperature in the chamber—combustion caused by the Biodiesel content which has a higher cetane number than diesel [42].

Increasing the concentration of biodiesel added to diesel can reduce particulate matter emissions into the atmosphere. This is an important contribution since many compounds that are considered carcinogenic and mutagenic can be associated with particulate matter, such as some polycyclic aromatic hydrocarbons and their derivatives [36, 43–45].

4.2 Engine compatibility and adaptations

The integration of high-biodiesel blends into conventional diesel engines presents several challenges and opportunities for optimization. Advances in engine technology are crucial for enhancing compatibility and performance when using biodiesel blends [31, 32].

4.2.1 Reduced wear and fuel system compatibility

- Material compatibility: Biodiesel can interact differently with engine materials compared to petroleum diesel, leading to potential issues such as increased fuel system degradation or corrosion. Modern engines and fuel systems are being designed with materials that are more resistant to biodiesel's properties, such as its solvent effect and higher lubricity. For instance, manufacturers are increasingly using materials like fluoropolymers and stainless steel in fuel system components to enhance durability and reduce maintenance needs [32].

Fuel type tested	Engine type	Emissions results	Engine performance results	Ref.
B20	Compression Ignition Engine	Reduced NOx and particulate matter (PM) emissions	Improved thermal efficiency and power output	[37]
B30	Diesel Engine	Lower CO2 and hydrocarbon emissions, higher NOx	Slight decrease in power output, improved fuel consumption	[38]
B10	Turbocharged Diesel Engine	Significant reduction in particulate matter (PM)	Enhanced engine torque and efficiency	[39]
B50	Heavy-Duty Diesel Engine	Substantial reduction in CO and PM, increase in NOx	Decreased engine power but improved operational stability	[40]
Diesel-Biodiesel Blend (B5)	Agricultural Diesel Engine	Reduced carbon monoxide (CO) and NOx emissions	Increased fuel efficiency and minor power decrease	[41]

Table 2.
Use of diesel/biodiesel mixture and impact on pollutant emissions and engine performance.

- Lubricity: Biodiesel has superior lubricating properties compared to petroleum diesel, which can reduce engine wear and extend engine life. High-biodiesel blends, particularly B100, can provide significant lubrication benefits, reducing the need for additional lubricating additives in the fuel [32].

4.2.2 Emission controls

- Advanced emission control systems: Engines running on higher biodiesel blends often require advanced emission control systems to address increased NOx emissions. Technologies such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) are employed to manage and reduce NOx levels effectively. These systems can be optimized to work efficiently with biodiesel blends, ensuring compliance with emission standards [33].

- Engine calibration and tuning: Recent developments in engine calibration and tuning enable engines to better handle biodiesel blends. Adjustments in fuel injection timing, pressure, and volume can optimize combustion and reduce emissions. These adaptations are crucial for maintaining performance and meeting emission regulations while using high-biodiesel blends [33].

5. Applications beyond transportation

Biodiesel's versatility extends beyond traditional transportation applications, offering solutions for sectors like aviation, marine shipping, and stationary power generation. These sectors are facing increasing pressure to reduce emissions, and biodiesel provides a renewable alternative to conventional fuels with a lower environmental impact. This section explores the potential of biodiesel in aviation, marine applications, and power generation, along with current research, commercial trials, and the advantages of adopting biodiesel in these industries [46–49].

5.1 Aviation and marine applications

The aviation and marine shipping industries are among the largest emitters of greenhouse gases, and both sectors are actively exploring alternatives to conventional fossil fuels. Biodiesel, in its pure form or blended with traditional fuels, offers significant potential to help reduce emissions and enhance sustainability in these fields. The aviation sector has begun to explore biodiesel, particularly as part of blended biofuels, to reduce its carbon footprint. Several key areas of development include:

- Sustainable aviation fuel (SAF): Biodiesel, especially when blended with kerosene, forms part of the SAF initiative, a key focus for reducing emissions in aviation. SAF is a broad category that includes biodiesel and other bio-derived fuels like hydroprocessed esters and fatty acids (HEFA) jet fuel. Research suggests that SAF can reduce carbon emissions by up to 80% compared to conventional jet fuel, depending on the feedstock used [46].

- Commercial trials: Several airlines have already conducted successful biodiesel trials. For example, KLM and United Airlines have used biofuel blends for transcontinental flights, demonstrating biodiesel's potential in aviation. Though these trials are still in the early stages, they show promising results for reducing aviation-related emissions [46, 47].

- Challenges: The primary challenge for scaling biodiesel uses in aviation is the high cost of production compared to traditional aviation fuels, as well as the need for extensive certification and safety testing before biodiesel can be fully integrated into regular operations [46, 47].

The maritime industry is another significant contributor to global carbon emissions, accounting for about 3% of total greenhouse gas emissions worldwide. Biodiesel is a promising solution for the industry, offering cleaner combustion and reduced emissions [47].

- Marine biodiesel blends: Marine vessels can use biodiesel blended with traditional marine fuels (such as B20 or B100) to reduce emissions of SOx, NOx, and PM (particulate matter), making it an attractive option for reducing the environmental impact of shipping [47].

- Commercial trials: Companies like Maersk and Stena Line have already started experimenting with biodiesel blends in large shipping vessels, reporting a reduction in CO_2 emissions by up to 15–20% when compared to conventional marine diesel [47].

- Regulatory support: International maritime organizations, including the International Maritime Organization (IMO), are setting stricter emissions standards, which is encouraging more research and development into alternative fuels like biodiesel for the marine sector [47].

5.2 Stationary power generation

Biodiesel's utility is not limited to transportation; it is also becoming a viable option for stationary power generation, including electricity production and industrial machinery. This section discusses the potential of biodiesel in replacing diesel fuel in generators and other stationary power applications [48, 49]. Biodiesel is already being used in stationary diesel generators, particularly in regions with limited access to centralized power grids. The use of biodiesel in power generation offers several benefits:

- Cleaner emissions: Biodiesel can significantly reduce emissions of SOx, CO2, and particulate matter when used in power generators. It also provides a renewable alternative to conventional diesel fuel, reducing dependence on fossil fuels and improving energy security [48, 49].

- Energy security: Biodiesel can be locally sourced and produced, offering a renewable energy solution that can reduce reliance on imported fossil fuels. This is especially valuable in remote or off-grid locations where conventional fuel delivery is expensive or unreliable [48, 49].

- Emergency and backup power: Biodiesel is a feasible fuel for backup generators, used in hospitals, data centers, and other critical infrastructure [49].

In addition to generators, biodiesel can be used in industrial machinery, such as construction equipment and agricultural machinery. These machines are typically powered by diesel engines, and the transition to biodiesel can provide environmental benefits while maintaining operational performance. Industrial machinery powered by biodiesel experiences lower maintenance costs and longer engine lifespans due to biodiesel's higher lubricity, which reduces engine wear and tear.

6. Policy and regulatory frameworks

The adoption of biodiesel as a sustainable alternative to fossil fuels is heavily influenced by policy and regulatory frameworks. These frameworks include global policies and incentives that promote biodiesel use, as well as sustainability standards that ensure biodiesel production meets quality and environmental criteria. This section provides an overview of these policies and standards and their impact on the biodiesel industry [50–52].

6.1 Global policies and incentives

Government policies and incentives play a pivotal role in encouraging the production and use of biodiesel. These policies vary by country but generally include subsidies, tax incentives, and renewable fuel standards aimed at increasing the market share of biodiesel and supporting its integration into existing fuel systems.

6.1.1 Subsidies

Subsidies are direct financial supports provided by governments to reduce the cost of biodiesel production and make it more competitive with fossil fuels. These subsidies can take several forms:

Production subsidies: Governments may offer financial assistance to biodiesel producers based on the volume of biodiesel produced. For example, the U.S. Biodiesel Tax Credit, originally set at $1.00 per gallon, helped lower production costs and encouraged biodiesel production. Similar subsidies are available in countries like Germany and Brazil [50–52].

Blending subsidies: Some governments provide subsidies to fuel blenders or distributors who incorporate biodiesel into petroleum diesel, thereby supporting the adoption of biodiesel blends. These subsidies can reduce the cost of biodiesel blends for consumers and incentivize their use in the market [50–52].

6.1.2 Tax incentives

Tax incentives are designed to reduce the tax burden on biodiesel production and consumption. These incentives include:

Tax credits: Producers and consumers may receive tax credits for using or blending biodiesel. For example, the U.S. Renewable Fuel Standard (RFS) provides tax credits for renewable fuels, including biodiesel [50–52].

Exemptions and reductions: Biodiesel may be exempt from certain taxes or receive tax reductions compared to petroleum diesel. This can include exemptions from fuel excise taxes or reductions in sales taxes on biodiesel [50–52].

6.1.3 Renewable fuel standards

Renewable fuel standards (RFS) mandate that a certain percentage of transportation fuels must come from renewable sources, including biodiesel. These standards are crucial for driving demand and ensuring the integration of biodiesel into the fuel supply:

U.S. renewable fuel standard (RFS): Administered by the Environmental Protection Agency (EPA), the RFS sets annual blending targets for biodiesel and other renewable fuels. It requires that a specific volume of biodiesel be blended into petroleum diesel each year [50–52].

European Union renewable energy directive (RED): The RED mandates that a certain percentage of transport fuels must come from renewable sources. This directive promotes biodiesel through blending targets and sustainability criteria [50–52].

6.2 Sustainability standards

Sustainability standards ensure that biodiesel production meets environmental and quality requirements, supporting its credibility and market acceptance. Key standards include ASTM D6751 and EN 14214 [50–52].

6.2.1 ASTM D6751

ASTM D6751 is the American Society for Testing and Materials standard for biodiesel. It sets forth the specifications for biodiesel quality, including:

Chemical properties: The standard defines limits for various chemical properties, including cetane number, sulfur content, and flash point, to ensure that biodiesel performs well in diesel engines and does not cause damage or operational issues [50–52].

Performance requirements: ASTM D6751 specifies performance requirements related to fuel stability, oxidation, and corrosion to maintain biodiesel's effectiveness and longevity in storage and use [50–52].

Impact on trade: Compliance with ASTM D6751 helps biodiesel producers meet quality requirements for the U.S. market and facilitates international trade by aligning with global quality standards [50–52].

6.2.2 EN 14214

EN 14214 is the European standard for biodiesel used in Europe. This standard includes:

Chemical and physical specifications: EN 14214 outlines specifications for various properties of biodiesel, including density, viscosity, and free fatty acid content, to ensure high fuel quality and compatibility with European diesel engines [50–52].

Sustainability criteria: EN 14214 incorporates sustainability criteria, including requirements for the reduction of greenhouse gas emissions and environmental impact from feedstock production, promoting the use of biodiesel from sustainable sources [50–52].

International trade: Adherence to EN 14214 allows biodiesel producers to access the European market and ensures that biodiesel meets the quality and environmental criteria required for importation and use in Europe [50–52].

7. Conclusions

Biodiesel technology has undergone significant evolution since its inception, reflecting broader shifts toward sustainable and renewable energy solutions. From its early reliance on edible feedstocks to the development of more advanced sources like microalgae and waste oils, biodiesel has consistently demonstrated its potential to reduce greenhouse gas emissions and provide a cleaner alternative to petroleum diesel. The advancements in biodiesel production, including improvements in feedstock selection, production methods, and engine performance, underscore its growing importance in global energy strategies. Despite these advancements, challenges remain, including the need for further optimization of production processes, improved engine compatibility, and enhanced economic feasibility. Future research will be pivotal in addressing these challenges, focusing on refining biodiesel-diesel blends, enhancing production efficiency, and exploring novel feedstocks. As governments and industries continue to prioritize renewable energy, biodiesel stands as a key player in the transition to a more sustainable energy landscape. Its ability to contribute to a closed carbon cycle, reduce dependence on fossil fuels, and support energy security makes it an invaluable component of future energy solutions. Biodiesel's journey from a niche alternative to a mainstream renewable energy source highlights its significant potential and ongoing relevance in addressing global environmental challenges. As technology and policy frameworks continue to evolve, biodiesel will likely play an increasingly prominent role in shaping a sustainable and resilient energy future.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 6

Sustainable Innovations in Biodiesel Plants: From Production to Environmental Impact

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Abstract

This chapter aims to explore the latest advancements in biodiesel plant technologies and their implications for sustainable development. It will delve into the various stages of biodiesel production, from feedstock selection to processing techniques, highlighting innovations that enhance efficiency and reduce environmental impact. The chapter will also examine the role of biodiesel in the broader context of renewable energy, addressing challenges and opportunities for scaling up production. By analyzing case studies and industry trends, the chapter will provide insights into the future trajectory of biodiesel plants and their significance in mitigating climate change while promoting energy independence and sustainable development.

Keywords: biodiesel, sustainability, green energy, seed plants, environmental impact

1. Introduction

This chapter provides a comprehensive overview of the pivotal role that biodiesel plays in the global shift toward renewable energy. It begins by emphasizing the significance of biodiesel as a sustainable alternative to conventional fossil fuels, highlighting its potential to reduce greenhouse gas emissions and enhance energy security. The chapter aims to explore the latest advancements in biodiesel production technologies, focusing on innovative feedstock selection, state-of-the-art processing techniques, and the integration of renewable energy sources within biodiesel plants. It also addresses the environmental impacts of biodiesel production, examining life cycle assessments, emissions control, and waste management strategies. Economic and policy considerations are discussed to provide a holistic view of the biodiesel industry, supported by case studies that showcase successful implementations and best practices. The chapter further delves into the challenges and opportunities associated with scaling up biodiesel production, offering insights into emerging technologies and future trends.

By setting these themes, the relevance in promoting sustainable development and mitigating climate change through biodiesel innovations has been delivered.

1.1 Overview of biodiesel and its importance

This section provides a foundational understanding of biodiesel, a renewable energy source derived from biological materials such as vegetable oils and animal fats. It outlines the chemical composition of biodiesel and explains how it serves as a sustainable alternative to traditional fossil fuels. The importance of biodiesel in addressing global energy needs and reducing greenhouse gas emissions is emphasized. Additionally, the section touches on the role of biodiesel in promoting energy security and supporting agricultural economies.

1.2 Objectives and scope of the chapter

The primary objective is to explore recent advancements in biodiesel production technologies and their contributions to sustainable development. This section defines the scope of the discussion, detailing the stages of biodiesel production that will be covered—from feedstock selection to processing techniques. It also highlights the focus on innovations that improve production efficiency and reduce environmental impacts. By setting the stage for the subsequent sections, this part underscores the chapter's relevance in the context of renewable energy and sustainable practices.

2. Feedstock selection for biodiesel production

2.1 Types of feedstocks: Edible vs. non-edible oils

Biodiesel production relies heavily on the type of feedstock used. Traditionally, edible oils such as soybean, canola, and palm oil have been the primary sources for biodiesel. For example, in the United States, soybean oil is a dominant feedstock, accounting for about 50% of biodiesel production. However, the use of edible oils raises significant concerns about food security and competition with food crops, leading to the exploration of non-edible oils. Non-edible feedstocks, such as Jatropha, Camelina, and used cooking oils, present an attractive alternative. Jatropha, for instance, can yield about 1590 liters of oil per hectare annually, without competing with food crops, as it can be grown on marginal lands. The shift toward non-edible oils helps mitigate the food vs. fuel debate and supports sustainable biodiesel production [1].

2.2 Advancements in feedstock development

Recent advancements in feedstock development focus on enhancing the oil yield and resilience of feedstock crops. Genetic modification and selective breeding have produced high-yield varieties of oilseed crops. For example, genetically modified Camelina can produce up to 38% more oil per hectare compared to its conventional counterparts. Algae, with its high oil content and rapid growth rate, has also garnered attention as a promising feedstock. Microalgae can produce 58,700 liters of biodiesel per hectare annually, significantly outperforming terrestrial crops [2]. Additionally, advancements in agricultural practices, such as precision farming and sustainable irrigation, have improved the efficiency of feedstock cultivation, reducing the environmental footprint of biodiesel production.

2.3 Sustainability considerations in feedstock selection

The sustainability of biodiesel production is intrinsically linked to the choice of feedstock. Sustainable feedstock selection involves evaluating factors such as land use, water consumption, greenhouse gas emissions, and biodiversity impacts. Life cycle assessments (LCAs) have shown that non-edible oils generally offer lower environmental impacts compared to edible oils. For instance, using waste cooking oil can reduce greenhouse gas emissions by up to 90% compared to fossil diesel [3]. Moreover, cultivating non-edible oil crops on degraded lands can enhance soil quality and prevent deforestation. In contrast, the expansion of palm oil plantations has led to significant deforestation and habitat loss in tropical regions. Thus, a shift toward sustainable feedstocks is critical for minimizing the ecological footprint of biodiesel production.

2.4 Economic implications of feedstock choices

The economic viability of biodiesel production is significantly influenced by feedstock costs, which account for 70–80% of total production expenses. Edible oils like soybean and canola are often subject to price volatility due to their use in both food and fuel markets. In contrast, non-edible oils and waste oils can offer more stable pricing and lower production costs. For example, the use of waste cooking oil can reduce feedstock costs by 30–40%, enhancing the economic competitiveness of biodiesel [4]. Additionally, the development of local feedstock supply chains can create job opportunities and stimulate rural economies, further supporting the economic sustainability of biodiesel production.

2.5 Policy and regulatory frameworks

Government policies and regulatory frameworks play a crucial role in shaping feedstock selection for biodiesel production. Subsidies, tax incentives, and mandates for renewable fuel usage can encourage the adoption of sustainable feedstocks. For instance, the Renewable Fuel Standard (RFS) in the United States mandates the blending of renewable fuels, including biodiesel, into the transportation fuel supply, promoting the use of diverse feedstocks [5]. Similarly, the European Union's Renewable Energy Directive (RED) sets sustainability criteria for biofuels, including restrictions on the use of high-risk feedstocks like palm oil. These policies aim to ensure that biodiesel production contributes to environmental sustainability and energy security.

3. Innovative processing techniques in biodiesel production

3.1 Transesterification process enhancements

The transesterification process, the primary method for producing biodiesel, involves reacting triglycerides from oils or fats with alcohol (usually methanol) in the presence of a catalyst (**Figure 1**).

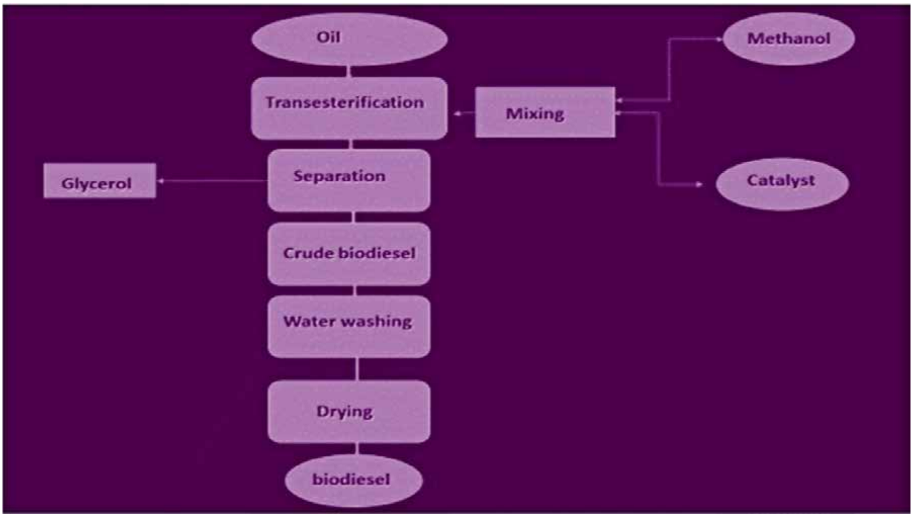

Figure 1.
Schematic flowsheet of the transesterification process for biodiesel production.

Recent advancements have focused on optimizing this process to improve yield and reduce costs. Techniques such as supercritical fluid extraction, ultrasonic-assisted transesterification, and microwave-assisted transesterification have shown promise. For example, ultrasonic-assisted transesterification can reduce reaction time and energy consumption by up to 50% while maintaining high conversion rates (over 95%). Supercritical methanol processing, although more energy-intensive, eliminates the need for a catalyst and significantly speeds up reaction, achieving yields above 98% in minutes [6].

3.2 Catalytic innovations and their impact

Catalysts play a critical role in the efficiency of the transesterification process. Traditional catalysts include sodium hydroxide and potassium hydroxide, which are effective but can lead to soap formation and require extensive purification steps. Innovations in heterogeneous catalysts, such as calcium oxide and solid acid catalysts, offer several benefits. These catalysts can be easily separated from the biodiesel product, reducing purification costs and environmental impact. For instance, the use of calcium oxide derived from waste eggshells has been shown to achieve a 97% biodiesel yield with improved process sustainability [7].

3.3 Process optimization for efficiency

Optimization of biodiesel production processes involves refining parameters such as temperature, pressure, and reaction time to maximize yield and minimize costs. Advanced computational methods, including machine learning and artificial intelligence (AI), are now being applied to model and optimize these processes. For example, AI-driven models can predict optimal reaction conditions that achieve high yields (up to 98%) with minimal resource use. Additionally, continuous flow reactors, which allow for the constant processing of reactants, have been developed to enhance scalability and efficiency, reducing processing time by over 60% compared to traditional batch reactors [8].

4. Integration of renewable energy in biodiesel plants

4.1 Solar and wind energy integration

Incorporating renewable energy sources like solar and wind into biodiesel production plants can significantly reduce their carbon footprint. Solar photovoltaic (PV) systems can provide the necessary electrical energy for operating machinery and heating reactors. For instance, a biodiesel plant equipped with a 1 MW solar PV system can meet up to 60% of its electricity needs, cutting down CO2 emissions by approximately 1500 tons annually [9]. Wind turbines can similarly provide a reliable energy source, especially in regions with high wind potential, contributing to further reductions in greenhouse gas emissions.

4.2 Biomass utilization for energy

Biomass, including agricultural residues and waste from biodiesel production, can be used to generate energy through combustion or anerobic digestion. Using biomass for energy not only provides a renewable energy source but also helps in managing waste effectively. For example, the glycerol by-product from biodiesel production can be anerobically digested to produce biogas, which can then be used to generate electricity and heat. This approach can cover up to 20% of the plant's energy requirements, enhancing overall sustainability [10].

4.3 Hybrid systems and their benefits

Hybrid energy systems that combine solar, wind, and biomass can offer the best of all worlds, ensuring a stable and continuous energy supply. These systems can be particularly effective in mitigating the intermittency issues associated with solar and wind energy. For instance, a hybrid system integrating solar PV, wind turbines, and a biogas generator can achieve a 24/7 renewable energy supply, significantly reducing reliance on fossil fuels. Studies have shown that such systems can lower energy costs by up to 30% while decreasing carbon emissions by more than 50% [11].

5. Environmental impact of biodiesel production

5.1 Life cycle assessment of biodiesel

Life cycle assessment (LCA) is a comprehensive method for evaluating the environmental impacts of biodiesel production from cradle to grave. LCAs consider factors such as feedstock cultivation, processing, transportation, and end-use emissions. Studies indicate that biodiesel can reduce lifecycle greenhouse gas emissions by 50–85% compared to conventional diesel. For example, biodiesel produced from waste cooking oil has a significantly lower carbon footprint (up to 90% reduction) than biodiesel derived from virgin vegetable oils [12].

5.2 Emissions and pollution control

Biodiesel combustion produces lower emissions of particulate matter, carbon monoxide, and hydrocarbons compared to conventional diesel. However, it can result in higher NOx emissions, which are a concern for air quality. Advanced emission control technologies, such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR), are being implemented to address this issue. For instance, using SCR can reduce NOx emissions by up to 90%, making biodiesel a cleaner alternative [13].

5.3 Waste management and by-product utilization

Effective waste management and by-product utilization are crucial for the sustainability of biodiesel plants. The primary by-product, glycerol, can be refined and used in various industries, including pharmaceuticals and cosmetics, and as a feedstock for producing chemicals like propylene glycol. Additionally, solid residues from feedstock processing can be used as animal feed or converted into biochar, which can improve soil health and sequester carbon. Implementing comprehensive waste management strategies can enhance the economic viability of biodiesel production while minimizing environmental impact. For instance, converting 100 tons of waste glycerol can produce approximately 50 tons of high-value chemicals, contributing to a circular economy [14].

6. Economic and policy aspects of biodiesel production

6.1 Cost analysis of biodiesel production

The economic viability of biodiesel production hinges on a thorough cost analysis that includes feedstock costs, processing expenses, and capital investments. Feedstock, often the largest expense, can vary significantly, with costs ranging from $0.30 to $0.70 per liter depending on the type used (e.g., waste oils are cheaper than virgin vegetable oils) [15]. Processing costs, which include the expenses for transesterification, catalysts, and energy, typically add another $0.20–$0.50 per liter. Additionally, capital investments for biodiesel plants can be substantial, with initial setup costs often exceeding $1 million for small to mid-sized facilities. The overall cost of producing biodiesel can range from $0.50 to $1.50 per liter, making competitive pricing crucial for market success. Innovations in feedstock development, process optimization, and waste management are critical to reducing these costs and enhancing profitability [16].

6.2 Government policies and incentives

Government policies play a pivotal role in shaping the biodiesel industry by providing incentives such as tax credits, subsidies, and mandates for biodiesel blending. For example, in the United States, the Biodiesel Tax Credit offers $1.00 per gallon of biodiesel blended with petroleum diesel, significantly impacting production economics. Similarly, the Renewable Fuel Standard (RFS) mandates the inclusion of renewable fuels in the national fuel supply, driving demand for biodiesel. In the European Union, the Renewable Energy Directive (RED) sets targets for renewable energy consumption, fostering a favorable market environment for biodiesel. These policies not only stimulate production but also encourage investments in research and development, leading to technological advancements and increased production efficiency [17].

6.3 Market dynamics and commercial viability

The biodiesel market is influenced by several factors, including crude oil prices, feedstock availability, and environmental regulations. High crude oil prices generally make biodiesel more competitive, while low prices can pose challenges. Feedstock availability is another critical factor, with agricultural policies and seasonal variations affecting supply and costs. The commercial viability of biodiesel also depends on its ability to meet quality standards such as ASTM D6751 and EN 14214, ensuring its suitability for use in modern diesel engines. Market demand for biodiesel is growing, driven by increasing environmental awareness and stringent emission regulations. However, the industry faces competition from other renewable fuels and energy sources, necessitating continuous innovation and efficiency improvements to maintain its market position [18].

7. Challenges and opportunities in scaling up biodiesel production

7.1 Technical and logistical challenges

Scaling up biodiesel production involves overcoming several technical and logistical challenges. One major technical challenge is ensuring consistent feedstock quality, as variations can affect the efficiency and output of the production process. Additionally, scaling up requires advanced technology to handle larger volumes of feedstock and produce biodiesel efficiently. Logistically, the transportation and storage of feedstocks and biodiesel pose significant challenges, especially given the perishability of certain feedstocks. Infrastructure development, including the establishment of new biodiesel plants and expansion of existing ones, requires substantial investment and planning. Addressing these challenges is essential for achieving economies of scale and reducing production costs [19].

7.2 Investment and funding opportunities

Investment and funding are critical for the growth of the biodiesel industry. Public and private sector investments can help finance the expansion of production facilities, research and development of new technologies, and the establishment of necessary infrastructure. Government grants and loans, venture capital, and partnerships with large energy corporations are potential sources of funding. For instance, in 2020, the U.S. Department of Agriculture announced grants and loan guarantees worth over $100 million to support biofuel production. Attracting investment requires demonstrating the economic and environmental benefits of biodiesel, as well as its potential for long-term profitability. Securing funding for pilot projects and commercialization efforts can pave the way for large-scale production [20].

7.3 Collaboration and partnerships

Collaboration and partnerships are crucial for overcoming the challenges associated with scaling up biodiesel production. Partnerships between universities, research institutions, and industry can drive innovation and technological advancements. Collaborations with agricultural sectors can ensure a steady supply of feedstocks, while partnerships with energy companies can facilitate the integration of biodiesel into the existing fuel supply chain. International collaborations can also play a significant role, enabling the exchange of knowledge, technology, and best practices. For example, the Global Bioenergy Partnership (GBEP) promotes international cooperation in bioenergy development. By fostering a collaborative approach, the biodiesel industry can leverage diverse expertise and resources to achieve sustainable growth and development [21].

8. Future trends in biodiesel plant technologies

8.1 Emerging technologies and innovations

The future of biodiesel production is being shaped by a host of emerging technologies and innovative practices designed to improve efficiency, reduce costs, and minimize environmental impacts. One significant advancement is the development of next-generation feedstocks, such as algae and genetically modified crops, which offer higher oil yields and lower land-use requirements compared to traditional feedstocks. For instance, microalgae can produce up to 30 times more oil per acre than conventional crops like soybeans. Another promising area is the use of waste materials, such as used cooking oil and animal fats, which not only provide a sustainable feedstock source but also help in waste management [22].

Innovations in catalytic processes are also crucial. Heterogeneous catalysts, which are more efficient and easier to separate from the final product than traditional homogeneous catalysts, are being increasingly used. For example, solid acid catalysts have shown potential in improving biodiesel yields and reducing production costs. Additionally, advancements in enzymatic transesterification, which uses lipase enzymes, offer a more environmentally friendly and efficient alternative to chemical catalysts [23].

8.2 Role of artificial intelligence and automation

Artificial Intelligence (AI) and automation are set to revolutionize biodiesel production by optimizing various aspects of the process. AI can be utilized to predict and optimize yields, reduce energy consumption, and enhance process control through real-time monitoring and data analysis. Machine learning algorithms can analyze vast amounts of data from biodiesel plants to identify patterns and predict equipment failures before they occur, thereby reducing downtime and maintenance costs.

Automation technologies, including advanced sensors and control systems, enable precise monitoring and control of production parameters such as temperature, pressure, and chemical concentrations [24]. This precision leads to more consistent product quality and increased operational efficiency. For example, automated systems can adjust the feedstock input and catalyst dosage in real-time based on the quality of the incoming materials, ensuring optimal reaction conditions and maximizing output.

8.3 Predictions for the next decade

Looking ahead, the next decade is likely to witness significant growth and transformation in the biodiesel industry. The global biodiesel market is projected to grow at a compound annual growth rate (CAGR) of around 5% from 2021 to 2030, driven by increasing demand for sustainable energy and favorable government policies. Advances in feedstock diversification, particularly the use of non-food crops and waste materials, will be critical in addressing sustainability concerns and improving the overall carbon footprint of biodiesel production.

Technological integration, including AI and automation, will play a pivotal role in enhancing production efficiency and reducing operational costs. The adoption of biorefinery concepts, where biodiesel plants produce multiple products (such as biogas and bioethanol) from the same feedstock, will become more common, contributing to economic viability and resource efficiency. Furthermore, policy and regulatory frameworks are expected to evolve, providing stronger incentives for renewable energy adoption and fostering innovation in the sector [25].

9. Implications for sustainable development

9.1 Environmental benefits

Biodiesel production offers significant environmental benefits, including a reduction in greenhouse gas emissions and decreased reliance on fossil fuels. Life cycle assessments (LCAs) have shown that biodiesel can reduce carbon dioxide emissions by up to 78% compared to conventional diesel [26]. The use of waste materials as feedstocks further enhances these benefits by diverting waste from landfills and reducing methane emissions from decomposition.

9.2 Economic impact

The expansion of the biodiesel industry can stimulate economic growth by creating jobs in agriculture, manufacturing, and research sectors. According to the National Biodiesel Board, the U.S. biodiesel industry supports over 60,000 jobs and adds billions to the economy annually. Developing countries, particularly those with abundant agricultural resources, can benefit economically by producing biodiesel for both domestic use and export [27].

9.3 Social and health benefits

Biodiesel production can also have positive social impacts by providing rural communities with new income sources and enhancing energy security. The reduced emissions of pollutants such as sulfur oxides and particulate matter contribute to improved air quality and public health, particularly in urban areas prone to smog and pollution.

9.4 Challenges and opportunities

While the benefits are substantial, challenges remain in achieving sustainable biodiesel production. Issues such as feedstock availability, land use competition, and the need for technological advancements must be addressed. However, these challenges also present opportunities for innovation and collaboration across sectors [28]. Continued research and development, supported by strong policy frameworks and investment, will be crucial in overcoming these barriers and fully realizing the potential of biodiesel as a sustainable energy source.

By addressing these various aspects, the chapter provides a comprehensive analysis of the future trends and sustainable development implications of biodiesel plant technologies, offering valuable insights for stakeholders in the renewable energy sector.

10. Conclusion and recommendations

The exploration of sustainable innovations in biodiesel plant technologies reveals a promising pathway for addressing the global energy crisis and mitigating environmental impact. From advanced feedstock selection to cutting-edge processing techniques and the integration of artificial intelligence and automation, the biodiesel industry is poised for significant growth and transformation. The chapter underscores the critical role of technological advancements in enhancing production efficiency, reducing costs, and minimizing the environmental footprint of biodiesel production. Furthermore, the economic, social, and health benefits associated with biodiesel production highlight its potential as a key component of sustainable development. By examining future trends and the implications for sustainable development, this chapter provides a comprehensive understanding of the current landscape and future prospects of biodiesel technologies, emphasizing the need for continued innovation and collaboration to fully harness the potential of biodiesel as a renewable energy source.

1. *Invest in research and development*: Governments and private sectors should increase funding for R&D to explore new feedstocks, optimize processing technologies, and develop efficient catalysts to improve biodiesel production.

2. *Promote algae-based biodiesel*: Encourage the cultivation and use of algae as a feedstock due to its high oil yield and minimal land-use requirements, which can significantly enhance the sustainability of biodiesel production.

3. *Implement AI and automation*: Biodiesel plants should adopt AI and automation technologies to optimize production processes, reduce energy consumption, and improve operational efficiency through real-time monitoring and data analysis.

4. *Enhance policy and regulatory support*: Governments should create favorable policies and incentives for biodiesel production, including subsidies, tax benefits, and renewable energy mandates to encourage industry growth.

5. *Develop waste-to-biodiesel programs*: Establish programs that promote the use of waste oils and fats as feedstocks, which can help in waste management and provide a sustainable source of raw materials for biodiesel production.

6. *Encourage public-private partnerships*: Foster collaborations between public institutions, private companies, and academic researchers to drive innovation, share knowledge, and accelerate the adoption of advanced biodiesel technologies.

7. *Focus on life cycle assessments*: Conduct comprehensive life cycle assessments (LCAs) for biodiesel production to continuously evaluate and improve the environmental impacts, ensuring that the processes remain sustainable and eco-friendly.

8. *Invest in biorefinery concepts*: Support the development of biorefineries that produce multiple products from the same feedstock, enhancing economic viability and resource efficiency while reducing waste.

9. *Educate and raise awareness*: Implement educational programs and campaigns to raise awareness about the benefits of biodiesel and sustainable energy, targeting both the general public and industry stakeholders.

10. *Strengthen global cooperation*: Encourage international cooperation and knowledge exchange to address common challenges, share best practices, and collectively advance the biodiesel industry toward a more sustainable future.

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Biodiesel Plants - Fueling the Sustainable Outlooks provides an approach to the crucial role biodiesel plants play in transitioning to a society less dependent on fossil fuels. Each chapter unveils a unique lens on the biodiesel production process, from the careful selection of feedstocks to the innovative technologies that are reshaping the industry's future. With a focus on sustainability, it highlights technological advancements that reduce the environmental impacts of biodiesel production while promoting a greener, more resilient economy. Aimed at scientists, engineers, policymakers, and all those who envision a cleaner, more sustainable tomorrow, it offers valuable insights for anyone seeking to understand the future of renewable energy and its positive impact on the environment.

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