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Review Article

Biodiesel Beyond Fuel: A Review of Expanding Applications and Embracing Circularity

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About Article

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ABSTRACT

Biodiesel, which is traditionally viewed as a cleaner alternative to fossil fuels, is also gaining new applications outside of energy. In this review, 182 peer-reviewed articles and patents retrieved via Google Scholar, Semantic Scholar, MDPI, ResearchGate, Scopus, ScienceDirect, among others were systematically synthesized concerning 2012-2025 as of August 2025. These 94 studies represent the percentage of traditional fuel applications, the 47 studies non-fuel applications (with 18 studies on green solvents, 16 on biodegradable lubricants, and 13 on specialty polymers), 28 studies into glycerol valorization into chemicals, e.g. of 1,2-propanediol, organic monomers and polymer additives, and 13 studies on circular economy strategies. Results demonstrate that biodiesel can be utilized as a raw material to develop quality and environmental-friendly products. Critical issues such as the cost of production, quality control, and regulatory gaps are also highlighted. Researchers, industry practitioners, and policymakers can use this review as a source of actionable insights by focusing on recent research, patents, and industrial developments significant to obtain a sustainable and circular bioeconomy.

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1. INTRODUCTION

The popularity of biodiesel as an alternative fuel has been supported by the fact that the world is increasingly concerned about the shortage of fossil fuels, the deterioration of the environment, and the necessity of a more efficient energy source (Babadi *et al.*, 2022; Kumar *et al.*, 2024). The possibilities of biodiesel are much broader than the transport sector where this tool is traditionally applied, and are aligned with the principles of the circular economy (Okpo & Edafiadhe, 2024; Sreeharsha *et al.*, 2023). Biodiesel is also becoming an accepted sustainable alternative to oil, and it has the potential to decrease fossil fuel dependence, energy security, and greenhouse gas emissions (Akpan *et al.*, 2023; Suzihaque *et al.*, 2022; Edeh, 2020). The rising biodiesel production in the world has been stimulating researchers and stakeholders in the industry to venture into value addition of both biodiesel and its products. The goal will be to optimise use of raw materials and by-products in the integrated production system, including glycerol and biomass. It is a broader perspective of a circular economy, where the idea is to reduce waste, recycle and optimise (Kirchherr *et al.*, 2017; Geissdorf *et al.*, 2017). Here, biodiesel is not just a renewable fuel, but a driver of sustainable industrialization, and an energy-flexible future. Akpan *et al.* (2023) assert that about 36 billion litres of biodiesel is produced worldwide by various countries using various raw materials such as edible oils, inedible oils, waste fats, algae oil, genetically modified microbes, and waste sludge oils. Benti *et al.* (2023) note that biodiesel consists of edible oils of sunflower, soy, soybean, palm fruits, linseed, and sesame oil that compose approximately 95 percent. Research work on life cycle analyses has shown that biodiesel can reduce greenhouse gas emissions by 78.45-86 percent compared to petroleum diesel (Xu *et al.*, 2022; Chandrasekhar *et al.*, 2012; Sheehan *et al.*, 1998). One of the most important environmental advantages of biodiesel to the environment is the fact that it substantially reduces emissions of particulate matter, hydrocarbons, and air toxins as opposed to petroleum-based diesel oil (Teixeira *et al.*, 2012; Sheehan *et al.*, 1998). This review, therefore, looks in more detail at how biodiesel and its by-products find new life in various sectors, from green solvents and specialty chemicals to advanced materials and lubricants. The objective of this review is threefold: firstly, to examine use of these non-fuel fuels and to highlight where impact of biodiesel is already present; secondly, to demonstrate how by-products such as glycerol can be transformed into high-value-added biofuel products; and thirdly, to examine how circular economy practices are integrated into biodiesel production. Drawing on recent studies, this review synthesises the latest thinking and developments in this area. Ultimately, the review provides practical insights for scientists, industry and policy makers working to unlock the full potential of biodiesel for a more sustainable future.

1.1. The Economic and Environmental Advantages of Biodiesel

Biodiesel has several benefits as compared to the traditional fossil fuels. Demirbas (2009) emphasized that the advantages of its use were the enhancement of energy security, reduced environmental impact, savings at the exchange rate, and substantial socio-economic advantages of its use, in particular, in rural areas, through job creation and enhanced health outcomes in the population. Biodiesel consumption also results in significant decreases in the production of harmful emissions, such as carbon monoxide, unburned hydrocarbons, and particulate matter (Sreeharsha *et al.*, 2023; Suhara *et al.*, 2024). Moreover, biodiesel contributes to the development of the carbon-neutral bio-economy and promotes sustainability (Sreeharsha *et al.* 2023). The addition of waste-based feedstocks, including waste cooking oil (WCO), to biodiesel production also increases its environmental usefulness by minimizing waste, cutting down production cost, and advancing the idea of a circular economy (Okpo & Edafiadhe, 2024). All these advantages make biodiesel an essential element of sustainable energy and economic growth plans. However, sustainability of these biofuels has been questioned over the past few years, especially with respect to food-fuel trade-offs, carbon accounting, and land use, as observed by Araujo *et al.* (2017). According to a report by Zulqarnain *et al.* (2021), using first-generation feedstocks to produce biodiesel may cause a food versus fuel crisis. This would lead to increased costs of the oils and biodiesel. On the same note, Kafuku & Mbarawa (2010) mention that there is a possibility that the prices of these resources will increase in case the current practices remain unchanged. As a fuel source, the production costs, cold flow properties, storage stability, and engine compatibility of biodiesel are still problematic (Sia *et al.*, 2020). Tesfa *et al.* (2010) identify high fuel viscosity as a major drawback of biodiesels as it may affect the performance of diesel engines. Due to these limitations, new innovations have increased the application of biodiesel and its byproducts way beyond their conventional role as alternatives to diesel. In order to substantiate the argument about the underutilization of biodiesel, Nabgan *et al.* (2022) have outlined a vast range of applications of biodiesel as an alternative source of fuel. As shown in Figure 1, biodiesel has proved to be versatile in many applications such as transportation, power generation plants, agricultural machines, and as a source of heat to residential and commercial boilers. Also, scientists have emphasized the possible feasibility of biodiesel in aviation.

Biodiesel has surged to unprecedented heights as an industrial solvent (Salehpour & Dube, 2008) and fuel filter (IFS, 2020). Research has indicated that the by-products and co-products of biodiesel are used in value-added biodegradable products, such as biodegradable plastics (Zhu *et al.*, 2013). Vivekananda *et al.* (2013) argue that pure glycerin, a by-product of biodiesel, has a wide range of uses in different industries including food, cosmetics and pharmaceuticals, among others. Such multifunctional applications in the exploitation of the previously untapped biodiesel potential can speed up the transition towards the more sustainable circular economy paradigm. According to Geissdorfer *et al.* (2017), the circular economy is a regenerative system that seeks to reduce resource use, waste, emissions, and the loss of energy by optimising the material and energy flows by means of slowing, closing, and narrowing the material and energy cycles. The EEA (2023) defines circular economy as an attempt to transform our economy, which is mostly linear (waste), into a closed-loop economy. In this transition, the impact of resource extraction, emissions, and

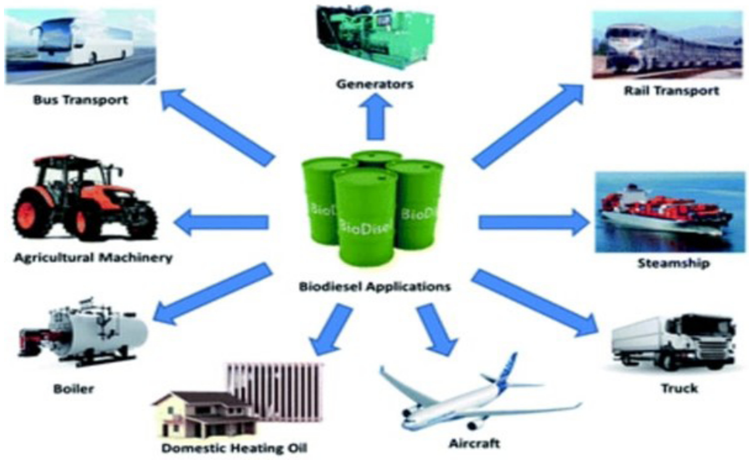

Figure 1. Biodiesel applications in some industrial sector (Nabgan *et al.*, 2022).

waste on the environment will be reduced, and material and energy use will be reduced (EEA, 2016). Circular economy prioritises resource optimisation, extends product lifespan, and advocates for practices like reuse, repair, refurbishment, and recycling (Econocom, 2022; CONTEC, 2024; Manickam & Duraisamy, 2019; Grigoryan Borodavkina, 2017).

2. LITERATURE REVIEW

2.1. Overview of the Production and Feedstock of Biodiesel

Biodiesel is mostly made by transesterification or esterification of a variety of bio-based feedstocks, such as vegetable oils, waste cooking oil-(WCO), and animal fat (Akram *et al.*, 2025; Tulashie *et al.*, 2025). One such resource has been WCO, which has gained more attention in recent years on the basis of its two-fold benefits, namely that it is a relatively cheap source of biodiesel feedstock, but also serves to alleviate the environmental issues caused by inappropriate disposal of oil. This is in line with the principles of circular economy, and the approach provides a sustainable waste valorization route (Okpo & Edafiadhe, 2024; de Carvalho Freitas *et al.*, 2022). Feedstocks used to make biodiesel are broadly divided into three generations. Examples of first-generation feedstocks are the edible oils i.e. soybean, palm and sunflower oils. Although such sources are technically efficient, their usage has been questioned because of the food versus fuel debate since they compete directly with food resources (Aderibigbe *et al.*, 2021). Conversely, second-generation feedstocks (WCO and lignocellulosic biomass) offer more sustainable alternative because they use non-food waste material, which also help in making it economically viable and environmentally friendly (de Carvalho Freitas *et al.*, 2022; Garg *et al.*, 2023). Even more promising are third-generation feedstocks and microalgae, in particular. They are rich in lipids, grow rapidly, consume little land and can absorb CO_2 in the cultivation process, which makes them a very renewable and efficient source of biodiesel (Aderibigbe *et al.*, 2021). Combined, these various feedstocks provide numerous options to develop biodiesel, each with their own benefits and problems. Further work and development on feedstock optimisation will be required to increase the production of biodiesel in a sustainable, economically viable manner.

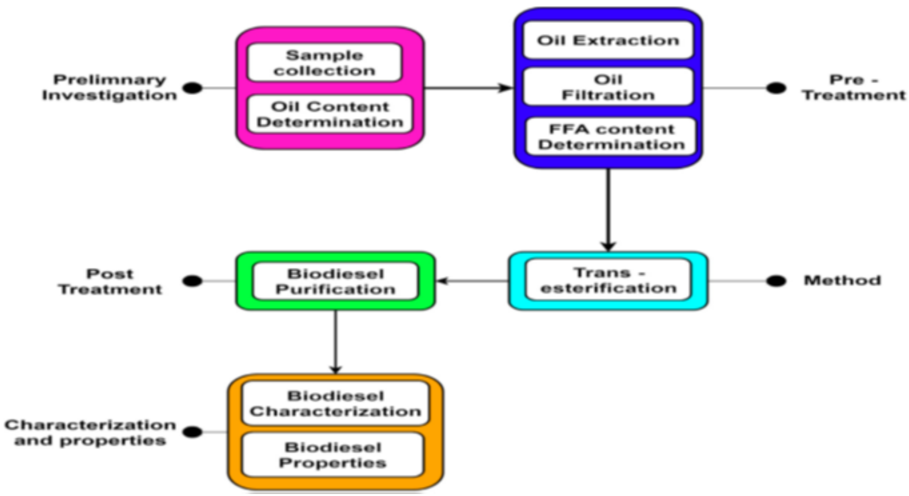

Figure 2. Biodiesel production flowchart (Kosuru *et al.*, 2024)

According to Figure 2 outlined by Kosuru *et al.* (2024), biodiesel manufacturing begins with the pre-treatment of the feedstock that involves the removal of impurities like water and free fatty acid-(FFA). The purified feedstock is then subjected to transesterification process in which it reacts with alcohol in the presence of a catalyst to produce biodiesel and glycerol. The mixture is afterwards divided and the biodiesel is washed again and dried. The final product (biodiesel) is stocked and can be distributed. The given process flow shows the key steps of operations, which are essential to provide consistent production of the high-quality fuel-grade biodiesel.

2.2. Role of Technology in Production of Biodiesel

Technology is important in enhancing the production of biodiesel through its emphasis on sustainability, efficiencies, and cost-effectiveness (Ismaeel *et al.*, 2024; Tabatabaei *et al.*, 2019). The technologies involved in biodiesel production are advancing rapidly as there is a necessity to deal with such issues as feedstock availability and costly production (Ismaeel *et al.*, 2024). One of the numerous processes that fall under the production technologies include the processing and optimisation of raw materials (Oh *et al.*, 2012). It is through technology that biodiesel production can be turned into renewable and economically feasible fuels (Ismaeel *et al.*, 2024). Enhanced methods are supposed to enhance energy security, rural development and low-carbon economy transition. The combination of machine learning (ML) and artificial intelligence (AI) is gaining popularity in order to optimise biodiesel production, and it has been providing holistic insights to address modern issues (Tabatabaei *et al.*, 2019). The AI driven optimisation and other emerging technologies should be embraced in order to produce biodiesel with a high level of efficiency (Tabatabaei *et al.*, 2019).

2.3. Production Technologies and Processes

Biodiesel production technologies encompass diverse feedstocks, reactors, catalysts and novel treatments (Oh *et al.*, 2012). Biodiesel manufacturing is mainly done through the process of transesterification, which consists of the reaction of alcohol and triglycerides catalysed by converters (Long *et al.*, 2021). The studies of the sources of renewable and sustainable energy are gaining popularity, and one of the aspects of reactor technology has a substantial influence on the effectiveness and capacities of biodiesel production (Yue *et al.*, 2024). Biodiesel production is increasingly being carried out with the help of processing intensification methods to overcome the issues of environmental impact, yield productivity, and feedstock flexibility (Mhetras & Gokhale, 2025). The recent progress in the methods of biodiesel production proves the creative approaches to enhance sustainability, economy, and productivity (Sreeharsa *et al.*, 2023).

2.4. Feedstock Processing and Optimisation

Feedstock processing is the essential step in the production of biodiesel that considerably affects the affordability and eco-friendliness of the entire process (Zheng *et al.*, 2025; Garg *et al.*, 2023). Feedstock optimization includes an assessment of a variety of feedstocks, marine and terrestrial, as well as edible and non-edible plant oils and waste cooking oil (Athar & Zaidi, 2020; Luke *et al.*, 2024). Markedly, waste oils and non-edible feedstocks are becoming progressively accepted as commercially viable feedstocks, with the added benefit of decreasing competition with food supplies directly, whilst facilitating the principles of circular economy (Sreeharsha *et al.*, 2023; El-Araby, 2024). Ozonolysis has been found to be one of the preprocessing techniques that can significantly increase cellulose accessibility in lignocellulosic biomass, thus its conversion efficiency (Bashir *et al.*, 2022). The biodiesel sector has developed to classify feedstocks into five generations with different properties and challenges of the processing that demand specific solutions to achieve the best outcomes (Luka *et al.*, 2024).

2.5. Emerging Production Technologies

In biodiesel production, the focus of emerging technologies is on a higher production rate of the products, reduction of energy use, and reaction kinetics (Ismaeel *et al.*, 2024). These involve incorporation of new catalysts like nanomaterial, metal-organic frameworks into transesterification process (Suhara *et al.*, 2024; Luka *et al.*, 2024). Quantum technologies, Continuous reactors, microreactors, and quantum reactor designs have increased levels of control and efficiency over conventional batch reactors (Saleh *et al.*, 2023). Generally, the external field, either microwave or ultrasonic irradiation, enhances the rate of transesterification reaction in the production of biodiesel (Ennetta *et al.* 2022; Beyene *et al.*, 2022). Other studies also discuss how genetic engineering could be used to maximise the production of lipids in algal feedstocks, once again enhancing the production of biodiesel (Luka *et al.*, 2024). To achieve the potential of biodiesel as an alternative to fossil fuels sources, there is a need to develop and optimise production technologies (Chuah *et al.*, 2017; Shalfoh *et al.*, in 2025). The advancement presents an opening to competitive and green biodiesel industry, in addition to solving the drawbacks of conventional processes.

2.6. Biodiesel applications beyond fuel

Biodiesel, which is mainly known as an alternative to fossil fuels, has a wide range of non-fuel uses due to its own characteristics and the fact that it is a clean fuel. Such applications cut across different industries, such as use as industrial solvents, lubricants, and cleaning agent constituents (Karis *et al.*, 2022). Even though biodiesel is mainly used as a fuel in compression ignition engines (Singh *et al.*, 2024; Patel & Brahmbhatt, 2022), its usage can also be referred to other areas. It has the potential to be utilized in power plants (Sentanuhady *et al.*, 2022), and in marine (Paulauskiene *et al.*, 2019; Noor *et al.*, 2018). Biodiesel can also be a source of bioplastics, pesticide formulations, and surfactants, taking advantage of its biodegradable and non-toxic properties and therefore fitting environmentally sensitive applications (Karis *et al.*, 2022). Furthermore, its use in many industries is being researched, and it is used in its properties besides its fuel abilities. According to Seifield (2025), the application of biodiesel is increasing globally not only in transporting motor vehicles on the road but also in specialised fields such as power generation and industrial lubricants as shown in Figure 3.

Figure 3. Applications of biodiesel in industry (Seifield, 2025).

2.7. Application of Biodiesel as Green Solvent

Recent reports support the possible use of biodiesel as a green solvent and lubricant, indicating low toxicity and biodegradability. The study sought to establish new bio-lubricants through an array of non-reactive raw materials. Bio-based lubricant production using desert date oil was studied, indicating it has the potential to be used in automotive vehicles and is superior to conventional lubricants at low temperatures (Adeoti *et al.*, 2024). This study demonstrates the potential of using native non-food-competing crops in sustainable industrial applications. According to Gadore *et al.* (2023), biodiesel presents a sustainable and environmentally-friendly alternative to conventional petroleum-based solvents. It can effectively replace traditional petroleum-based diesel in various applications where petrodiesel is currently used (Kumar Metal Industries, 2024). Biodiesel offers several advantages over its oil-based counterparts, such as biodegradability, low toxicity, high flash point, low vapour pressure, high solubility, low viscosity and water insolubility (Li *et al.*, 2016). These properties make biodiesel a suitable choice for industrial processes such as cleaning, coating and paint thinning (Kumar Metal Industries, 2024). Biodiesel's solvent capabilities make it useful in industrial cleaning processes (Karis *et al.*, 2022). Although the viability of biodiesel as a solvent has been demonstrated in technical studies (Chemat *et al.*, 2012), its wider use is hampered by its relatively higher cost compared to conventional solvents. According to the SGBiofuels report (2016), biodiesel (or its derivatives) can remove low-toxicity oils, paints and adhesives, often replacing more hazardous petrochemical solvents. However, various studies have explored the potential of biodiesel as a solvent for a wide range of applications, highlighting its efficiency and environmental benefits. A study by Fernandez-Alvarez *et al.* (2007) investigated use of biodiesel as bioremediation technique to treat coastlines affected by the heavy oil spill. According to their research, biodiesel showed promise as a workable solvent for soil remediation because of its FAME (Fatty Acid Methyl Ester) content, which successfully reduced the viscosity of crude oil spills. In another research, it was discovered that the application of FAME obtained out of rapeseed oil as solvents in polymerisation resulted in the adoption of cleaner technologies (Salehpour & Dube 2008).

Moreover, experiments by Zhang *et al.* (2019), as well as Li *et al.* (2016), have shown that soybean oil methyl ester (SBME) is an effective form of biodiesel, which was as effective as the traditional solvents in isolating neutral compounds and chemicals. These findings underscore the utility of biodiesel as green alternative solvent in a number of extraction processes. According to Richards *et al.* (2010), biodiesel may be used to substitute highly toxic paint removal products. It is probably most appropriate to use in non-critical, smaller-scale uses. Moreover, the residues of adhesives, including duct tape, can also be removed using biodiesel. Due to the excellent solvency properties of B100, it can be applied to clean oil/greasy engine parts and other machine components. Although biodiesel production is more expensive, the exclusive solvents properties, combined with its environmental advantages, including biodegradability and low toxicity, make it a potential alternative to conventional oil-based solvents in many industries. Despite the technical benefits of replacing oil-based solvents with vegetable oil-based FAME, cost-prohibiting factors might remain (Mohsin *et al.*, 2017).

2.8. Application of Biodiesel as Lubricant

There has been a significant development in the hunt of biodiesel-derived lubricants with the need to find alternatives to traditional lubricants, which require sustainability and high performance. It is also interesting in its use as a lubricant, which is a potential replacement of petroleum-based products, particularly in applications where biodegradability is a requirement (Karis *et al.*, 2022). Another landmark research conducted by Hu *et al.* (2005) yielded interesting results on lubrication potential of biodiesel. In their study, they found out that raw unrefined biodiesel possessed superior lubricating properties than its refined cousin. This surprising discovery cast doubt on the long-held assumption that refined biodiesel makes a better lubricant. Their study established that crude biodiesel has a potential of being a viable option that exploits its inherent lubricating properties without necessarily undergoing the long refining processes. Since there is an increasing demand of high-performance and environmentally safe lubricants, Hu *et al.* (2005) have demonstrated an interesting way of tapping the untapped potentials of raw biodiesel in lubrication. Various chemical catalysts have been used throughout the synthesis process so that the properties of these fluids could be tailored to suit a particular need (Li *et al.*, 2019; da Silva *et al.*, 2013).

2.9. Specialty Chemicals Application of Biodiesel

The rich supply of raw glycerol has made the researchers and industries to venture into various uses of this product and discover new ways of utilisation and sustainable exploitation of available resources. Although glycerin finds extensive use in chemicals, pharmaceuticals, foods and cosmetics, the manufacturers face an economic challenge of attaining the desired purity of glycerin (Bhatia *et al.*, 2021; Kolesarova *et al.*, 2011; Pachauri & He, 2006). Studies show that biodiesel can be used as a precursor to biopesticides (Mohsin *et al.*, 2020; Purkait & Hazra, 2020; 2017; Min & others. 2015). Bio pesticides are sometimes less toxic and more biodegradable as compared to synthetic pesticides. Moreover, the literature indicates that it is possible to use biodiesel drilling fluid, rather than diesel fuel (Li *et al.*, 2016; Wang *et al.*, 2012). According to Wang *et al.* (2012), drilling fluids prepared using biodiesel have better performance properties than conventional oil-based drilling fluids and have outstanding environmental sustainability. The research demonstrated that such new formulations of drilling fluids, based on renewable sources of biodiesel, are superior to traditional formulations in terms of operational efficiency and performance. It is interesting to note that not only biodiesel-based drilling fluids possessed better functional characteristics, but they also did not conflict with the principles of environmental protection and reduced the ecological consequences of drilling activities. A blend of operational efficiency and environmental sustainability is a potential solution to the industry that will satisfy the technical demands of the industry as well as the environmental factors. In another study, further conducted by Ahmed *et al.* (2021), important findings were revealed in an exploration of the application of biodiesel in an implementation of drilling mud. Their study demonstrated that the rheology and filtration characteristics of drilling mud formulations with the introduction of biodiesel significantly change towards better values. Noteworthy is the fact that biodiesel based lubricants possess outstanding lubricating properties, which is one of the significant attributes that translate to the smooth drilling process. The operative limits of biodiesel are limited to temperatures below 120 °C, however, since it may get unstable at higher temperatures. Besides, the high biodegradability of these biodiesel formulations was noted by Ahmed *et al.* (2021), which aligns with the conservation of resources and environmental sustainability. Cumulative findings of the study give biodiesel as a viable and green alternative to drilling mud. Biodiesel as a drilling mud component is one possible avenue to achieving both economic and environmental objectives in the industry as it increasingly focuses on sustainability and ensuring regulations are actually met.

2.10. Agricultural Applications

Biodiesel is a green alternative to the conventional chemicals, which can be used in the agricultural sector to develop pesticides (Karis *et al.*, 2022). Also, due to its surfactant properties, it can be utilized in numerous ways in agriculture i.e. in enhancing the penetration of leaf sprays. In the Seifield (2025) report, biodiesel is sometimes used in production of bio-based fertilizers, which is an example of it in the circular economy. Recent studies have centred on the use of biodiesel as a raw material in agriculture, especially as a medium to deliver ecologically friendly pesticide formulations. The main advantages of biodiesel as a solvent or carrier of liquid pesticide systems compared to the conventional oil-based solvents are low volatility, high flash point, and low toxicity. Such qualities enhance the efficiency of the spraying process as well as reduce the threat to the environment and the health of the population. Biodiesel is, therefore, a viable green chemistry approach in sustainable agriculture (Purkait & Hazra, 2020).

2.11. Biodiesel Application in Bitumen, Asphalt and Construction Materials

There is a great deal of research underway concerning new and innovative uses of biodiesel beyond its more conventional transport applications. One of the new areas of interest that have gained a lot of attraction is the incorporation of biodiesel in the development of building materials and bituminous composites. There are also possibilities of incorporation of biodiesel in building materials and bitumen which may help in the creation of green infrastructure as well as the exploration of new methods of utilizing this renewable resource. One of these attempts, the exploration of utilizing the biodiesel by-products as asphaltic acid additives (Sun *et al.*, 2016), has been rather positive. Their research revealed that these by-products have the potential to enhance the performance of asphalt, particularly at lower temperatures and thereby make it more convenient to utilise in road construction in low temperature conditions. Raman *et al.* (2015) research recommends that bio-oil may enhance the quality of asphalt binder and make the process of paving asphalt cheaper. Biorejuvenators are applied to recover the characteristics of oxidized and thermally cycled and fatigued asphalt mixtures bitumen (Cabette *et al.*, 2023). The use of biodiesel instead of oil bitumen partially can decrease the negative impact of road construction on the environment. In addition, biodiesel-treated pavements show improved performance in different weather conditions. Moreover, glycerin, a by-product of biodiesel, is used as a dust-retardant in construction sites and in unpaved roads. Its use effectively binds dust particles, reducing the particulate matter in the air and thus improving air quality (Yan & Hoekman, 2012). Although various reports and patented technologies recognize the potential efficacy of this glycerine derived from biodiesel in dust control applications, the existing literature does not generally contain comprehensive guidance on parameters and methods to be used. It should be underlined that the integration of biodiesel in bitumen and building materials is an evolving field of research and development. As the studies currently being carried out and new technologies become available, the potential uses of biodiesel in these sectors will likely increase.

2.12. Advanced Bio-based Materials and Polymers

The chemical components of biodiesel, in particular the fatty acid methyl esters (FAME), are increasingly being used as building blocks for sustainable construction. The focus has shifted from simple applications to more complex, value-added products. The glycerol byproduct was utilized to make a biodegradable plastic that showed good soil and photodegradation qualities (da Silva *et al.*, 2022). This study highlights the concept of a biorefinery where one feedstock is transformed to multiple valuable products.

2.13. Applications of glycerol: A key biodiesel co-product

2.13.1. Application in Bioplastics Synthesis

Conventional plastics made of oil are a severe threat to the environment because it cannot be returned to the environment and could be very destructive when improperly disposed of. This has seen researchers put extra efforts to seek alternative materials that can replace these traditional plastics as the idea of environmental concern is on the rise. It is through these efforts that the use of bioplastics has turned out as the potential and sustainable solution and bioplastics have gained immense attention among both the scientific communities and the industry stakeholders. What makes them essential is their ability to encourage the circular economy and help tackle the issue of plastic pollution faced across the world. Biodiesel by-products can be utilised as plasticisers or monomers when producing bioplastics. As an example, glycerin, the by-product of biodiesel, has an application in the chemical processing industry (Rastegari *et al.* 2019; Yang *et al.* 2012). Studies have established that the conversion of glycerin produced in the production of biodiesel to polyhydroxyalkanoates (PHAs) has the prospects of leading to significant returns in terms of environmental protection (Zhu *et al.* 2013). Nonetheless, biodiesel is an encouraging form of adding bioplastic to the act of sustainability and waste management. Enhancing a synergistic relationship between scientific work and technological innovations, the bioplastics industry may find an efficient way in order to move toward the sustainable and environmentally-friendly future and strike a proper balance between the satisfaction of human demands and nature conservation. Current research into the prospects of biodiesel in new markets is the use of biodiesel as bioplastics feedstock (Karis *et al.*, 2022). The chemical components of biodiesel, especially the fatty acid methyl esters (FAME) are increasingly being explored as the source of sustainable structures in the manufacture of high-value products. Simple fuel applications are no longer being prioritized but instead there is production of complex and high-value products. Literature has proved that old cooking oils can be transformed into biodiesel and bioplastics and the by-product denotes glycerol that can be used to produce biodegradable plastics that can exhibit better soil and photodegradability (da Silva *et al.* 2022). This type of integrated approach is the best example of the principle of a biorefinery where the efficiency and sustainability of the process are maximized by producing several high-value products out of the same source of renewable raw material. In addition, research is underway to improve the characteristics of biodiesel to exactly fit into non-fuel applications, thus gaining marketability and improved environmental benefits.

2.13.2. Polymer Synthesis

Biodiesel manufacture produces large volumes of crude glycerol, an efficient and inexpensive renewable fill material precursor of polymers. Its versatility and abundance combined with its ability to perform numerous functions means that it can be used in many chemical reactions. Interestingly, it is known that glycerol crude is utilized to create alkyd resin, which are very common in the manufacturing of paints and coatings, due to their superior film formation and adhesion properties. Polyesters are also synthesized with it (glycerol co-diacid) and are potentially used in biodegradable packaging materials and biomedical applications. Moreover, glycerol-based polyols have been effectively synthesised into polyurethane foams, which are crucial in the insulation and cushioning processes (Wang *et al.*, 2024). Moreover, carbon-based glycerol is used to make polyhydroxyalkanoates (PHAs), a family of biodegradable and bio-based plastics. Others uses are production of bio-based adhesives, which are a cost-effective, renewable alternative to traditional petroleum-based adhesives, and polyglycerol, which finds use in pharmaceuticals and cosmetics due to its emulsion and lubricating properties (Wang *et al.* 2024).

2.13.3. Synthesis of Bio-Based Monomers

Another application is the use of the crude glycerol as a multi-purpose precursor in the production of a number of high value bio-essential monomers. These products include 13-propanediol (13-PDO), used in the manufacture of polytrimethylene terephthalate (PTT), a biodegradable polyester finding use in textiles and packaging, and 23-butanediol, which could be used as a platform chemical to manufacture plastics, and as a biofuel additive. Moreover, sugar alcohols (mainly erythritol, mannitol and arabitol) are very common sugar alcohols that can be obtained from crude glycerol and commonly used as low calorie sweeteners and functional food ingredients. Dihydroxyacetone (DHA) is yet another compound based on glycerol and is being extensively used in cosmetic products (e.g., self-tanning products) and pharmaceutical preparations (Wang *et al.*, 2024). These improvements demonstrate the opportunities in glycerol crude as a source of sustainably produced raw materials in a bio-based economy that will generate monomeric building blocks and polymers.

2.13.4. Applications in 1,2-Propanediol Synthesis

The key biodiesel production by-product, glycerol, is generated in large volume, and when disposed off carelessly, this leads to economic and environmental issues. Converting this surplus glycerol to high value chemicals, e.g., 1,2-propanediol (1,2-PDO) is a sustainable and economically feasible way to increase the overall efficiency and profitability of biodiesel production systems (Zhou *et al.*, 2020). 1,2-PDO is a versatile compound, which has broad industrial uses, e.g., as a solvent and humectant in pharmaceutical and cosmetic products, as an ingredient of antifreeze and de-icing fluids, Two main routes of reaction are mostly followed in the catalytic conversion of glycerol to 1,2-PDO, which are (i) dehydration and oxidation via acetol intermediate and (ii) dehydration and oxidation via glyceraldehyde intermediate. The most common of these is dehydration-hydrogenation because it consumes relatively low amounts of energy and can be used with a diverse range of catalysts (Zhou *et al.*, 2020). Further study on catalyst design and reaction optimisation is needed to enhance selectivity, yield and scalability of this transformation to industry.

2.13.5. Application in Catalyst Templates

One study has examined the use of the biodiesel by-product waste glycerol as a green templating reagent to produce mesoporous ZSM-5 zeolite catalysts (Kumar *et al.*, 2024). The work shows a valuable roadmap of how to turn waste into something valuable and how to develop catalysts, and there is hope of scaling to other zeolites or biomass waste by-products.

2.14. Circular Economy Integration of Biodiesel

The biodiesel sector is investigating how it can adopt the principles of circular economy to enhance the economic and environmental sustainability of the sector (Popovic & Radivojevic, 2022). The by-products of the production process, e.g. glycerol, may be converted into high value products, which makes the production of biodiesel more economical (Elsayed *et al.*, 2022; Chilakamara *et al.*, 2022). The use of waste materials (waste cooking oil, WCO) as raw materials in order to minimise pollution and support the circular economy is also observed (Okpo & Edafiadhe, 2024). The main aspect of enhancing the sustainability of biodiesel systems is the life-cycle assessment, waste-to-value transformation, and circular economy (Okpo & Edafiadhe, 2024; Longo *et al.*, 2023). The principles of the circular economy are applied in biodiesel systems, which are the minimization of waste and the maximization of the use of resources (Popovic & Radivojevic, 2022; Vinayak *et al.*, 2024). This can be done in a number of ways; through waste materials being used as a feedstock, conversion of byproducts to useful products, and implementation of closed-loop systems (Okpo & Edafiadhe, 2024; Ye *et al.*, 2024). The application of WCO as a biodiesel raw material complies with the principles of a circular economy and zero discharges (Hosseinzadeh-Bandbafha *et al.*, 2022). The use of waste materials makes biodiesel production more economically viable and at the same time solves the environmental problems that are related to waste disposal (Okpo & Edafiadhe, 2024; Santander-Bossio *et al.*, 2025).

2.15. Biodiesel Life Cycle Assessment

Life Cycle Assessment (LCA) has gained importance in evaluating the effect and the eco-friendliness of biodiesel production as a whole regarding the environmental effect (Delgado, 2025). It enables policy makers and scientists to compare the environmental impacts of various feedstocks, production systems and processing procedures on biodiesel. As an illustration, a number of studies have demonstrated that using waste cooking oil (WCO) as a raw material can deliver huge environmental benefits of first generation biofuels (Patel & Singh, 2024). Likewise, LCA methods were used to assess the use of biodiesel made using jatropha curcas, with the effect of modifying scientists to allow them to comprehend environmental compromises more (Thakur & Chandel, 2021). Fine-tuning of the manufacturing process itself is also performed with the aid of LCA. As an example, the emission and energy use can be minimized by modifying the particular treatment conditions of their application of WCO use (Corral-Bobadilla *et al.*, 2022). Models like cradle-to-gate created by Torres *et al.* (2020) track the environmental factor until the moment when the biodiesel exits the plant. In addition, the LCA can be used to compare the impact of different treatment methods of how by-products affect the outcomes on sustainability (Torres & Macken, 2021).

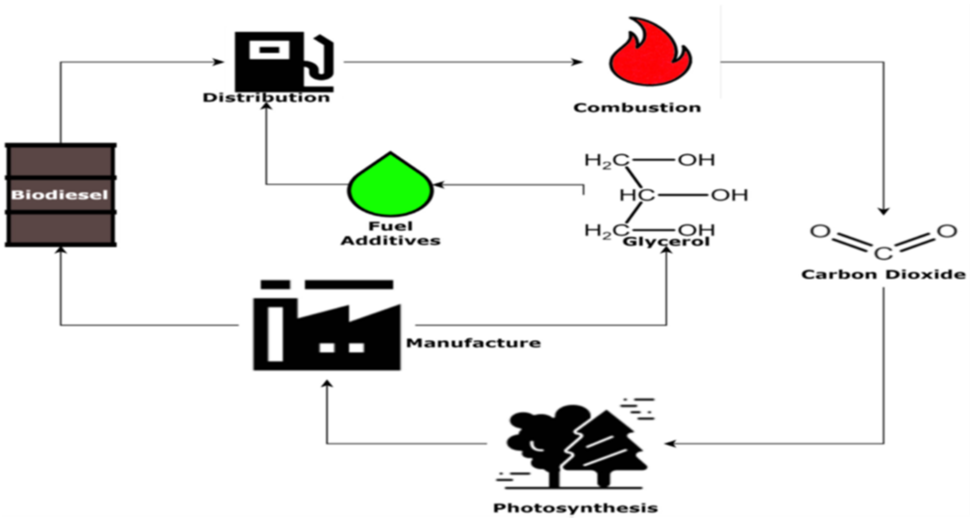

Figure 4. Biodiesel life cycle (Kosuru *et al.*, 2024).

The life cycle of biodiesel generally starts at the production of the oil-containing crops or the harvesting of the used cooking oils, as shown in the figure developed by Kosuru *et al.* (2024). These feedstocks undergo extraction and transesterification, which involves conversions of such materials into biodiesel and glycerol through licensed alcohol and catalysts. The biodiesel is purified and ready to distribute. The thing that is notable in this life cycle is the environmental advantage of carbon recycling: The carbon dioxide emitted when fuel is consumed is partially reabsorbed by plants during the growth process that contributes to the creation of a more balanced, closed cycle of carbon. In the bigger perspective, integrating LCA with circular economy principles and waste-to-value approaches can provide an effective means of making the production of biodiesel more sustainable. Using the waste materials, transforming the byproducts into resources, and constantly monitoring environmental impact, the biodiesel business can become both environmentally and financially sustainable (Okpo & Edafiadhe, 2024; Thompson, 2024). As shown in Figure 4 by Kosuru *et al.* (2024), production of oil-rich crops or collection of spent oils typically forms the first step of the life cycle of biodiesel. Extraction and transesterification are processes that are applied to these feedstocks using alcohol and a catalyst agent to turn them into a mixture of glycerol and biodiesel. The biodiesel is cleaned of impurities and then set to be distributed. In this life cycle, the fact that its combination with plants provides a partial consumption of the amount of carbon dioxide (CO_2) emitted when fuel is combusted in its use, to facilitate a more closed, balanced carbon cycle, makes it significant with regard to the environment. The combination of LCA and waste-to-value strategies and concepts of a circular economy in the long term will offer a powerful mechanism to raise the level of biodiesel manufacturing sustainability. Development of waste, transformation of byproducts to useful products, and periodic assessment of how biodiesel operations impact the environment are ways the biodiesel sector can make advancements toward eco-friendly and economic sustainability (Okpo & Edafiadhe, 2024; Hosseinzadeh-Bandbafha *et al.*, 2022; Thompson, 2024).

2.16. Biodiesel in Circular Economy: Challenges and Emerging Opportunities

Despite the common understanding of biodiesel as a sustainable alternative to fossil fuel, its possibilities go far beyond fuel tanks, especially when the perspective of the circular economy is taken into consideration (Gao *et al.* 2022; Marchetti & Gebremariam, 2021). However, to harness such potential, a number of technical, economic, and regulatory issues must be addressed.

2.16.1. Technical Challenges

The longstanding ways of manufacturing biodiesel e.g., through vegetable oils/ animal fats conversion, tend to be energy-intensive and come with significant expenses (Elgharbawy *et al.*, 2025). Such techniques also rival food production and have ensued the issue of sustainability (Mim *et al.*, 2025). Raw material selection has a massive influence on criterion of quality, cost, and sustainability of the biodiesel (Babadi *et al.* 2022). Moreover, natural resources may be strained by the process of obtaining feedstocks and sometimes hazardous chemicals are involved (Bidir *et al.*, 2021). But the emergent technology such as advanced reactors, the production based on microalgae, and processes assisted by microwave and ultrasound are demonstrating the potential to increase the cost-efficiency of biodiesel and clean up the process (Zhang *et al.*, 2021; Ramos *et al.*, 2022).

2.16.2. Economic and Market Barriers

The prohibitive price of production and scarcity of appropriate raw materials serve as the key challenges to the spread of biodiesel (Yatish *et al.*, 2025). What adds to this is the market uncertainties that include the unstable prices of oil and a debate on the issue of food or fuel (Sowan *et al.*, 2023). To render biodiesel economical. A thorough cost-benefit analysis, better access to cheaper sources of raw materials and better processing technologies is required (Bidir *et al.*, 2021; Ramos *et al.*, 2022). Economic research is needed to be able to comprehend economics and efficacies of the different biodiesel technologies. Scalability of circular economy activities in terms of financial viability raises a significant issue and needs to be cost-benefit effective, that is, capital investment cost-wise and operation costs (Ramos *et al.*, 2022).

2.16.3. Regulatory and Policy Considerations

Assistance of governments is very important in the development of biodiesel. In most locations, however, the rate is being hampered by poor policies and enforcement, as well as inadequate infrastructure (Mehra & Goel, 2025; Mukonza & Nhamo, 2016). Effective and transparent policy frameworks, which are friendly to biodiesel, ought to be established to propel investments, innovation, and incorporation of biodiesel in the wider sustainability agenda (Shabbir *et al.*, 2023).

2.16.4. Emerging Opportunities

Nevertheless, interest in alternative fuels is on the increase throughout the global market due to increasing oil prices and the need to cut down emissions. Among other things, biodiesel is also less polluting and biodegradable in addition to being renewable (Elgharbawy *et al.*, 2025; Vethathirri *et al.*, 2021). What is more thrilling is the turn to the possibility of using waste materials like agricultural residues, organic waste, and other material, most of which do not even get a mentioning as raw materials. This will not only eliminate waste; it is also completely compatible with the idea of circular economy (Damian *et al.*, 2024; Zivkovic *et al.*, 2017). The development of nanotechnology can also lead to further opportunities as it enhances the catalytic converter leading to efficiency in the processing result (Mehejabin *et al.*, 2024).

3. METHODOLOGY

This review used a systematic approach to the literature to examine the various applications of biodiesel beyond fuel, glycerol value addition, and circular economy policies. A total of 182 publications and patents, including the period of 1998 to 2025, mostly between 2012 and 2025, were extracted in Google Scholar, Semantic Scholar, MDPI, ResearchGate, Scopus, and ScienceDirect. The Boolean operators like OR, NOT were used to refine the searches that included such keywords as biodiesel production, non-fuel applications, glycerol valorization, biodegradable lubricants, green solvents, and circular economy. The inclusion criterion was peer-reviewed studies in English language involving biodiesel in terms of its fuel and non-fuel uses, glycerol use, or circular economy approaches; impractical, duplicative, or methodologically inadequate research was not included. The identified studies were filtered, and information was retrieved about the type of application, feedstock, process parameters, glycerol conversion, and application of the circular economy. The articles were classified into the following sections: fuel applications (94), non-fuel applications (47; green solvents 18, biodegradable lubricants 16, specialty polymers 13), glycerol valorization (28), and circular economy strategies (13), referred to as detailed, repeatable, and measurable coverage of biodiesel research.

4. RESULTS AND DISCUSSION

As Figure 5 indicates, most of the biodiesel studies focus on its fuel application, with 94 studies showing its use as an already established source of renewable energy. In addition, the figure indicates the rising interest in other non-fuel uses (47 studies), glycerol valorization (28 studies), and circular economy practices (13 studies), implying the prospects of a broader utilization of biodiesel. Figure 6 gives more details about the non-fuel applications, where 18 studies report on the use of biodiesel as a green solvent, 16 on the use of biodiesel as a biodegradable lubricant and 13 on the use of biodiesel as producing specialty polymers. Collectively these figures suggest that although biodiesel is still largely thought of in terms of its role in energy production, there is a rising interest in its potential as a sustainable industrial feedstock and means of realising circular economy solutions.

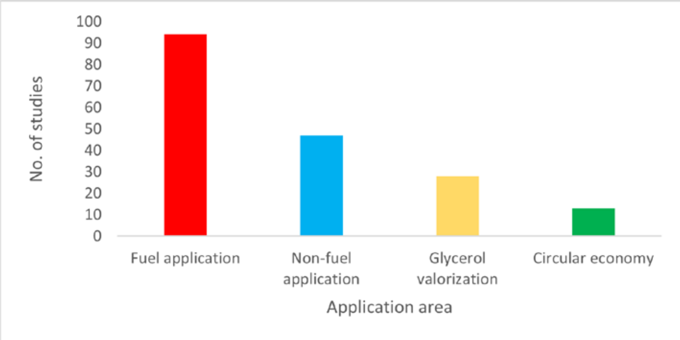

Figure 5. Overview of biodiesel research application

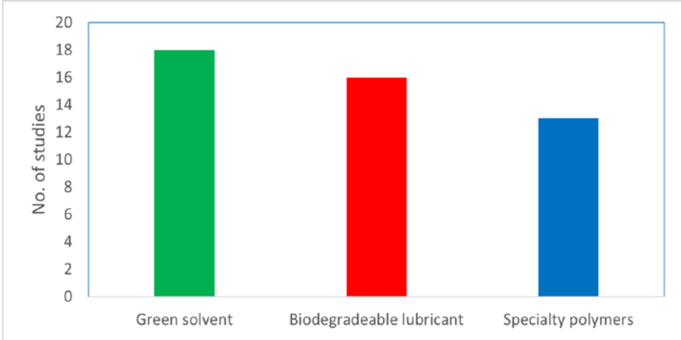

Figure 6. Breakdown of non-fuel biodiesel application

Altogether, the data shows that although biodiesel is still mostly researched as a fuel, there is a growing interest in unconventional applications and sustainability models, which introduces its potential beyond fuel applications within a circular bioeconomy. The quantified results of biodiesel applications reflect not only the improvement but also the existing gaps that need to be filled in, thus directly answering the purpose of the review. All of this evidence leads to the conclusion that biodiesel has a strong potential of contributing to creation of a sustainable and circular bioeconomy.

5. CONCLUSION

The presented systematic review of 182 publications and patents released between 1998 and 2025 and focusing on 2012-2025 shows that biodiesel is a highly versatile bio-based product whose use can be extended far beyond the use as an automotive fuel. Among them, 94 studies confirmed its renewable energy potential, 47 studies emphasized its non-fuel applications, and 28 studies on glycerol valorization which could be used in green solvents, biodegradable lubricants, specialty polymers, and premium chemicals. A review of 13 studies on the topic of circular economy interventions indicates that there are opportunities to develop the efficiency of the use of resources, reduce the quantity of waste, and optimize economic sustainability. These improvements notwithstanding, there are still challenges such as the expensive cost of production, quality control problems, and lack of regulation. In sum, the evidence indicates that biodiesel can play a meaningful role towards a sustainable, circular bioeconomy and that of the industry practitioners, researchers, and policymakers interested in maximizing its overall environmental, economic, and industrial potential.

FUTURE RESEARCH

The presented systematic review of 182 publications and patents released between 1998 and 2025 and focusing on 2012-2025 shows that biodiesel is a highly versatile bio-based product whose use can be extended far beyond the use as an automotive fuel. Among them, 94 studies confirmed its renewable energy potential, 47 studies emphasized its non-fuel applications, and 28 studies on glycerol valorization which could be used in green solvents, biodegradable lubricants, specialty polymers, and premium chemicals. A review of 13 studies on the topic of circular economy interventions indicates that there are opportunities to develop the efficiency of the use of resources, reduce the quantity of waste, and optimize economic sustainability. These improvements notwithstanding, there are still challenges such as the expensive cost of production, quality control problems, and lack of regulation. In sum, the evidence indicates that biodiesel can play a meaningful role towards a sustainable, circular bioeconomy and that of the industry practitioners, researchers, and policymakers interested in maximizing its overall environmental, economic, and industrial potential.

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