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A review of major trends, opportunities, and technical challenges in biodiesel production from waste sources

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ABSTRACT

As the world addresses the increasing demand for sustainable energy solutions, biodiesel has surfaced as a viable alternative to conventional fossil fuels. The expansion of biodiesel feedstock plantations, particularly palm oil in tropical regions, can lead to deforestation, loss of biodiversity, and significant carbon emissions from the destruction of carbon-rich ecosystems. That is why this article focuses on biodiesel production from waste sources in order to maintain balance in the ecosystem. This review paper discusses the global energy landscape and the need for renewable and environmentally friendly alternatives. It explores the various waste sources in depth that are investigated for biodiesel production, comprising waste cooking oil, animal fats, algae, and other organic residues. Each feedstock is analyzed for its viability, challenges, and economic feasibility in biodiesel production. A critical assessment of different biodiesel production methods, such as transesterification, pyrolysis, thermochemical conversion, anaerobic digestion, thermal cracking, hydro-treating and enzymatic processes, is presented, highlighting the key factors influencing their efficiency and scalability. Recent developments to enhance waste-derived biodiesel production's sustainability and economic viability to meet UN Sustainable Development Goals are also highlighted. Furthermore, the environmental impact of biodiesel, including greenhouse gas emissions and land use, is discussed to provide a holistic understanding of its ecological footprint. The biodiesel from waste sources can significantly increase the brake thermal efficiency of the engine along with a substantial decrease in emissions like CO and HC. However, the NOx and CO_2 emissions are increased with the application of biodiesel from waste sources. The CO_2 and NOx emissions can be reduced by exhaust gas recirculation and selective catalytic reduction techniques. The paper also addresses regulatory frameworks and standards governing biodiesel production from waste sources, emphasizing the need for harmonized policies to encourage widespread adoption. The paper concludes by outlining future research directions and potential breakthroughs that could further enhance biodiesel production's effectiveness, sustainability, and scalability from waste sources. Waste Cooking Oil (WCO) and animal fats are currently the most economically feasible options for biodiesel production due to their low cost and established collection and processing infrastructure. Algae present high potential but require technological advancements and cost reductions to become economically viable. This review aims to assist researchers, policymakers, and industry stakeholders in advancing the utilization of waste materials for biodiesel production, promoting a more sustainable energy landscape.

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Nomenclature

BMEP	Brake Mean Effective Pressure
BP	Brake Power
BSEC	Brake-Specific Energy Consumption
BSFC	Brake-Specific Fuel Consumption
BSN	Bosch Smoke Number
BTE	Brake Thermal Efficiency
CAGR	Compound Annual Growth Rate
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPP	Cylinder Peak Pressure
EGT	Exhaust Gas Temperature
FAME	Fatty Acid Methyl Ester
FP	Flash Point
HC	Hydrocarbon
HRR	Heat Release Rate
IDP	Ignition Delay Period
IEA	International Energy Agency
KOH	Potassium Hydroxide
KV	Kinematic Viscosity
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
NaOH	Sodium Hydroxide
NOx	Oxides of Nitrogen
RNG	Renewable Natural Gas
SDG's	Sustainable Development Goals
SFC	Specific Fuel Consumption
UNEP	United Nations Environment Program
WAF	Waste Animal Fat
WCO	Waste Cooking Oil

1. Introduction

The global energy landscape is characterized by a heavy reliance on fossil fuels, such as coal, oil, and natural gas, which have been the primary energy sources for over a century. However, this dependence has significant environmental, economic, and geopolitical consequences, driving the urgent need for renewable energy alternatives. Fossil fuels account for about 80 % of the world's energy consumption [1]. They are major contributors to greenhouse gas emissions, leading to global warming and climate change [2]. Global energy demand continues to rise, driven by population growth, urbanization, and economic development, particularly in emerging economies. The distribution of fossil fuel resources is uneven, leading to geopolitical tensions and dependencies. Energy-importing countries are vulnerable to supply disruptions and price volatility. The transition to renewable energy alternatives is essential for addressing the current global energy landscape's environmental, economic, and geopolitical challenges. Embracing renewables helps combat climate change and promotes sustainable development, energy security, and economic prosperity [3]. As technology advances and costs continue to decline, renewable energy is poised to play a pivotal role in the future global energy mix. According to [4], the total global utilization of diesel has increased from 3.5 million tonnes in 2010 to 3.9 million tonnes by 2019. In the Asia Pacific region, countries such as China, Japan, and Malaysia, diesel consumption rose from 1.1 million tonnes in 2010 to 1.4 million tonnes by 2019 [4]. This highlights the need for viable diesel alternatives to address the escalating worldwide consumption. Biodiesel, a promising biofuel, has emerged as a pivotal player in this pursuit, offering a cleaner and more environmentally friendly substitute for conventional fossil fuels. Biofuels are generally more eco-friendly in terms of biodegradable, sulfur-free and non-toxic nature in comparison with other traditional fuel sources [5]. Biofuels contribute to the achievement of Sustainable Development Goals 7 (affordable and clean energy) and 13 (climate action) of the United Nations [6]. Global demand for biofuels is expected to increase by 41 to 53 billion liters, or 28 %, from 2021 to 2026 [7]. Fig. 1(a) displays the yearly comparison between 2005 and 2035 for sector-wise energy consumption. It can be observed that the trend is rapidly shifting from fossil fuel sources to alternate energy sources [8]. Fig. 1(b) displays the increasing trend of global marketed energy and CO_2 emissions from 2005 to 2030 [8,9].

Harnessing the potential of waste materials addresses the critical issue of waste management and contributes to a circular and sustainable approach to bioenergy production. The major waste sources that can be utilized for biofuel production are agricultural residues, industrial residues, municipal waste, waste cooking oil, waste animal fats, waste animal bones, and algae. According to available data, nearly 998 million tons of agricultural waste are generated yearly, the majority of which is either disposed of in landfills or incinerated, resulting in negative environmental impacts [10]. Agri-waste burning worldwide represents nearly 25 % of agri-biomass production [11]. Furthermore, the amount of agricultural residue produced globally is equivalent to nearly 50 billion tons of oil, according to the United Nations Environment Program (UNEP) [12]. Agricultural wastes encompass materials produced throughout the agricultural value chain, arising as raw materials, byproducts, or end products from various activities and processes. Once these materials reach a point where they are no longer viable for use, they are deemed as waste and are subsequently discarded and disposed of. Hence, agricultural biomass for energy production has substantial

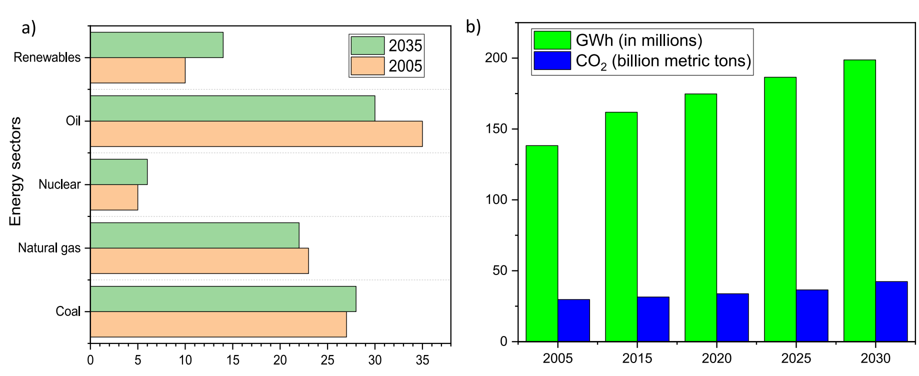


Fig. 1. A) sector-wise global energy consumption, b) yearly global marketed energy and co_2 emissions [8,9].

potential to replace or provide a viable alternative to conventional fuels. The International Energy Agency (IEA) reports a significant surge in annual oil prices alongside projections indicating a staggering 25 % rise in global energy demand from 2017 to 2040 [13]. Biodiesel is a liquid fuel that is burnt in internal combustion engines, much like conventional diesel. On the other hand, solar power harnesses energy from sunlight through photovoltaic cells, wind power captures energy from wind using turbines, and hydroelectric power generates electricity from flowing water by turning turbines. In short, biodiesel does not require specialized infrastructure, but other renewable energies require significant infrastructure facilities to be fully operational. Asia Pacific industrial waste management market scope was predicted to be worth USD 183.06 billion in 2022. Over the forecast span from 2023 to 2029, the Asia-Pacific industrial waste management market is anticipated to exhibit robust growth, with a projected compound annual growth rate (CAGR) of 6.6 %, culminating in a value of USD 268.65 billion by 2029 [14].

Using waste industrial oil to produce biodiesel can not only prevent improper disposal issues of waste oils, preventing environmental issues but also prove to be a viable alternative for fuel. As urban populations swell globally, managing municipal solid waste (MSW) is swiftly becoming challenging due to the common practice of landfilling or incinerating our waste often leads to adverse environmental impacts. Numerous studies have shown that the municipal solid waste that originates in developing countries is significantly from households (55 – 80 %), followed by market or commercial areas (10 – 30 %) [15]. Globally, MSW generation is expected to increase to 3.40 billion tonnes by 2050 [16]. With increasing population, land fillings are expected to get limited over time. Additionally, practices like waste disposal in landfills or dumpsites can impact groundwater by allowing leachate to leak [17]. Therefore, using municipal waste to generate biofuel is greatly beneficial. The market for used cooking oil was valued at US$ 6.1 billion worldwide in 2022. The IMARC Group projects that this market will experience a compound annual growth rate (CAGR) of 6.3 % from 2023 to 2028, reaching US$ 8.9 billion [18]. The production of biodiesel from leftover cooking oil, fish oil, and bones is a progressive and ecologically sound approach to waste management and renewable energy production. By recycling materials that would otherwise be wasted, this strategy offers an environmentally responsible alternative to traditional fossil fuels and helps mitigate environmental contamination. Utilizing leftover cooking oil, fish oil, and leftover bones to produce biodiesel demonstrates an impressive convergence of efforts between environmental preservation, sustainable energy generation, and waste minimization. This integration is a step in the right direction toward promoting a sustainable and ecologically friendly future.

The meat and poultry sectors are experiencing significant growth on a global scale. The rising population has spurred increased production of meat products to meet the growing demand for food. The annual meat and poultry production in the USA has approached 43.42 million tons, while in the Caribbean and Latin America, it stands at 38 million tons. The EU produces approximately 30 million tons, Sub-Saharan Africa 11.10 million tons, Australia 598 million tons, China 84.89 million tons, and India boasts a production of 1,323.5 million heads. [19]. In addition to the consumable products, the meat and poultry sectors produce significant quantities of animal by-products. These non-edible materials account for approximately 40 to 60 % of the livestock. Consequently, it has been reported that approximately 27.8 million tons of slaughterhouse waste are discarded annually in North America. Similarly, in the European Union, the discarded non-edible materials from the meat and poultry industries represent roughly 29.41 % of the 17 million tons of slaughterhouse by-products generated each year. These non-edible livestock wastes are predominantly utilized as raw materials across various industries, including tanning, textiles, detergents, fertilizers, and biofuels [20,21]. Turning waste animal fat into biodiesel is an ecologically conscious way to turn a food production byproduct into a substantial and sustainable energy source. By carefully managing organic waste, the use of leftover animal fat for biodiesel production reduces environmental pollution while simultaneously reducing dependency on finite fossil fuels. The conversion of animal fat waste into biodiesel is an example of the importance of applying sustainable practices in the energy and waste management domains. It offers a tangible means of turning waste into a valuable resource and promoting a more sustainable energy environment.

More than 50,000 recognized species of microalgae can flourish under varying water, soil, and sunlight conditions [22]. Through the absorption of solar energy, microalgae have the capacity to generate bio-oil. The increasing popularity of microalgae biodiesel production stems from its potential to combat climate change. Given its promising prospects as a renewable fuel for vehicles, microalgae are increasingly being directed towards this avenue. Algae have several excellent qualities, making them a suitable feedstock for biodiesel production. These qualities include their considerable lipid content and quick growth rate, which offer a range of appealing advantages for the environment. Growing algae to produce biodiesel avoids competing with important food crops and is environmentally flexible enough to be used in non-agricultural land and wastewater environments. The production of biofuels from algae is a viable, long-term, and expandable biofuel option that has significant potential for reducing the emission of greenhouse gases while also promoting global energy security and preserving essential resources.

The development of biofuel generations reveals different feedstock sources and associated technology paths (see Fig. 2). First-generation biofuels are produced by fermentation and transesterification processes using edible substrates such as corn, sugarcane, and edible oils. However, due to their reliance on consumable crops, which increases competitiveness for food supplies, they have innate sustainability problems. The second-generation biofuels, on the other hand, use alcohol and biomass-to-liquid technology to focus on non-edible materials such as woody biomass and waste from agriculture. This shift successfully addresses environmental issues and significantly reduces concerns about food competitiveness. Third-generation biofuels are made from algae and are produced using solvent extraction, transesterification, and supercritical fluid extraction techniques. They are more productive, need less space on land, and can be produced using a wider range of fuel types. Looking ahead, the theoretical fourth generation explores new fields, such as genetically modified plants, microbiological systems, and sophisticated waste disposal routes, with a focus on improved conversion procedures. With cutting-edge technology, this innovative period aims to achieve carbon neutrality, strengthened sustainability, and groundbreaking breakthroughs in the production of biofuels, denoting a revolutionary step towards ecologically responsible and optimized biofuel production paradigms. Biodiesel production involves glycerol formation as a by-product, which can be used to synthesize various useful products like acrolein, hydrogen, ethylene glycol, acetol, and propylene glycol (1,3-propanediol and 1,2-propanediol) from reforming and dehydration and hydrogenolysis reactions of glycerol conversions [23].

The present study embarks on an extensive review through the realms of biodiesel production from waste sources; hence, it becomes evident that the pursuit of sustainable energy solutions has never been more imperative. The synthesis of biodiesel from unconventional and often overlooked waste streams not only presents a promising avenue for reducing environmental burdens but also underscores the innovation and adaptability inherent in the field of bioenergy. Beyond its ecological advantages, this emerging frontier in biodiesel production holds the potential to transform waste management practices and contribute significantly to the global transition towards greener and more resource-efficient energy alternatives. Delving deeper into the intricacies of waste-based biodiesel synthesis in the subsequent sections, the review study anticipates uncovering novel insights and methodologies towards sustainable alternative fuel for automotive.

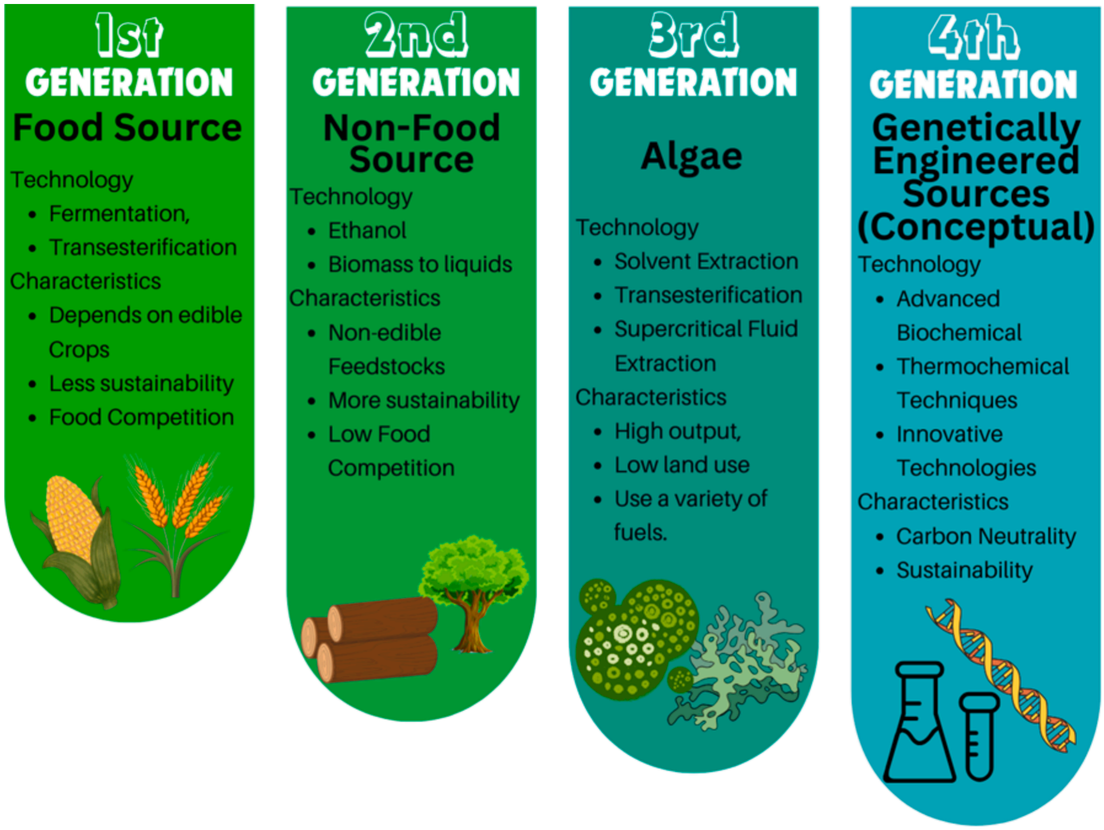


Fig. 2. Distinct generations of biodiesel feedstocks.

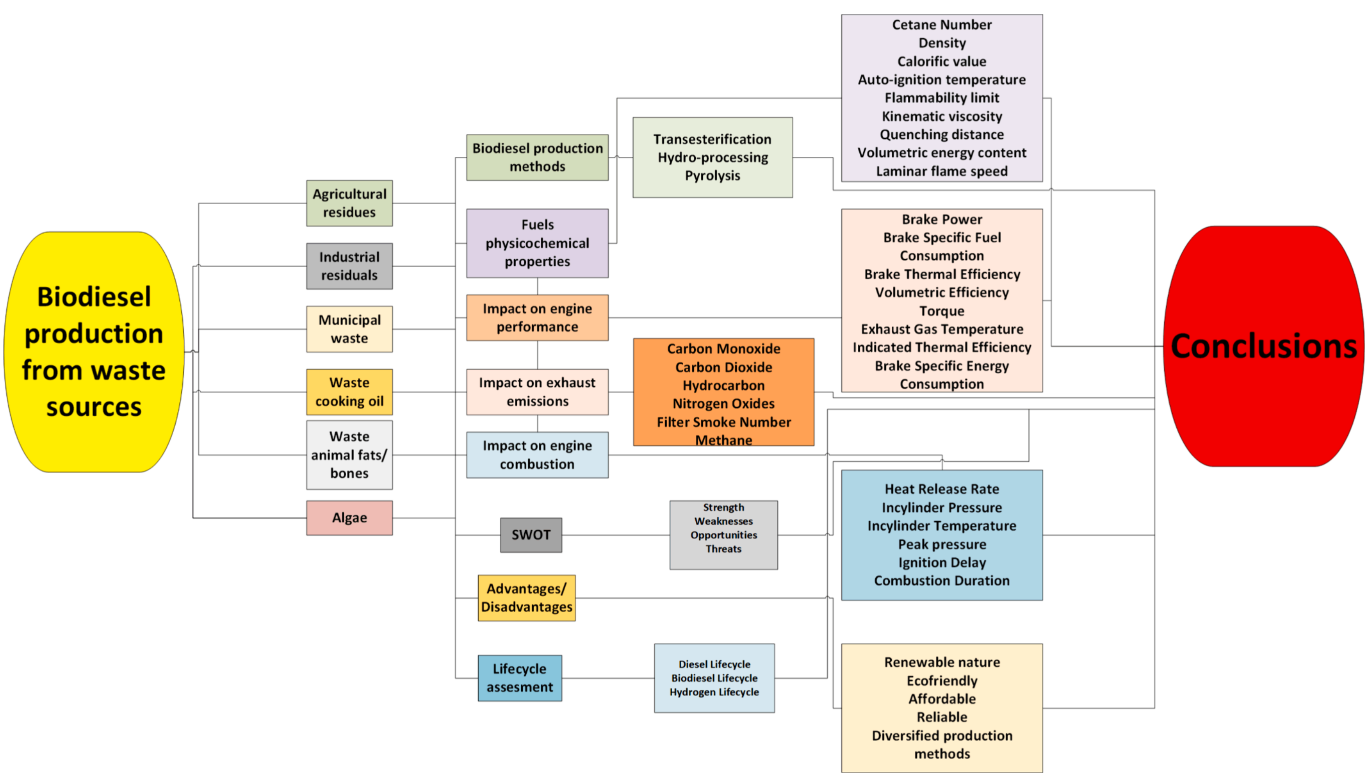


Fig. 3. Main constituents of the review article.

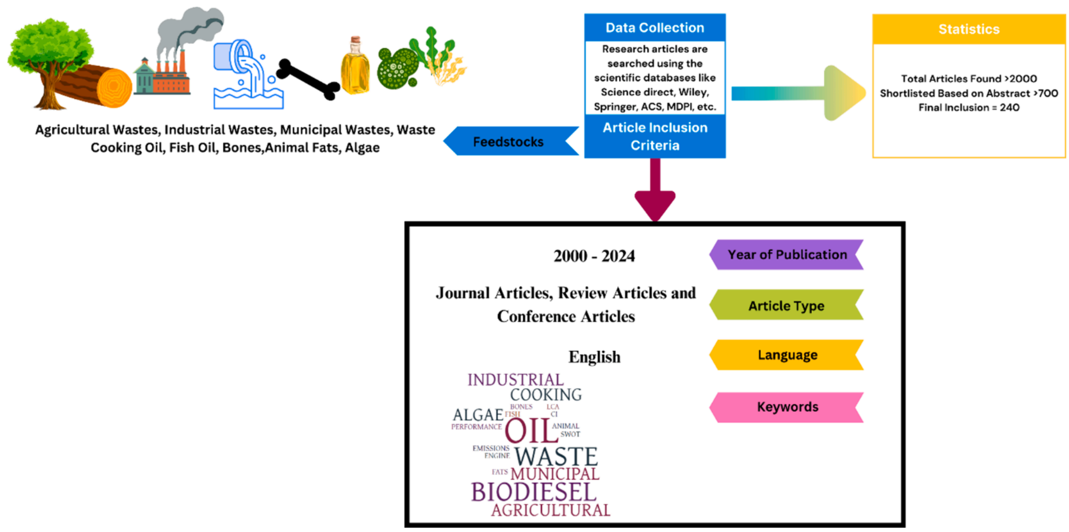


Fig. 4. Bibliometric Analysis.

2. Methodology

The methodology employed in this review article on biofuel production from waste sources follows a comprehensive and systematic approach to gathering, analyzing, and synthesizing the existing literature. The initial phase involved an extensive literature search done through various academic databases, including but not limited to PubMed, ScienceDirect, and Google Scholar. The keywords such as "biofuel," "waste sources," "renewable energy sources," and specific waste types are used to identify relevant articles. The inclusion criteria encompass peer-reviewed research articles, review papers, and conference proceedings published within a specified timeframe from 2000 to 2024. The selected studies are thoroughly assessed for their relevance to biofuel production from waste materials. Subsequently, a critical evaluation is conducted to extract key findings, methodologies, and technological advancements in the field. The collected information is then organized chronologically and thematically to present a coherent narrative. Additionally, a qualitative synthesis approach is employed to highlight the main trends, challenges, and opportunities in biofuel production from waste sources. The methodology employed in this review ensures a comprehensive and up-to-date analysis of the existing state of research in this dynamic and crucial area of renewable energy development. Fig. 3 entails the main constituents of the review study. As shown in Fig. 4, the articles to be reviewed are searched from scientific databases like Science Direct, Wiley, Springer, ACS, and MDPI. A total of more than 2000 articles were found using the keywords: Biodiesel, waste sources, algae, industrial waste, municipal waste, agricultural waste, animal fat, waste cooking oil, fish oil and bones. The inclusion criteria were that the article should be in English, the year of publication should be between 2000 and 2024, and the first priority should be given to the journal articles that were published recently. After reading the abstract and title, more than 700 articles were segregated, among which 236 articles were selected for this review.

3. Production methods

In this section, the production cycle for biodiesel derived from different waste sources is discussed. Researchers have explored various methods for biodiesel production from waste sources, including hydroprocessing [24], supercritical fluid extraction [25], and microbial conversion [26]. However, to date, transesterification and enzymatic processes are the most commonly employed and efficient techniques [27]. Transesterification is a commonly used method for converting various types of waste into biodiesel, requiring pretreatment to remove impurities across all waste sources. It is effective for lipid-rich materials such as agricultural waste, waste cooking oil, and algal lipids, ensuring efficient conversion to biodiesel [28]. The chemical reaction involved in the Transesterification process is given in Fig. 5 [29]. For municipal and industrial waste, it necessitates sorting and is suitable for certain byproducts like glycerol [30]. Animal waste needs to undergo rendering before transesterification [31]. Despite differences in specific pretreatment requirements and the efficiency depending on the waste's nature, the fundamental process involves reacting fats or oils with alcohol in the presence of a catalyst.

Transesterification is the most common method for producing biodiesel. It involves converting triglycerides (fats/oils) into fatty acid methyl esters (FAME) and glycerol by reacting them with an alcohol (typically methanol) in the presence of a catalyst. Triglycerides react with methanol (or another alcohol) in the presence of a catalyst (see equation 1). The catalyst can be base (NaOH or KOH), acidic (H_2SO_4), or

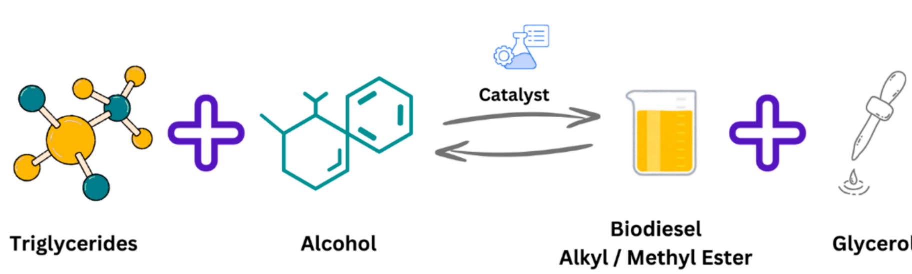
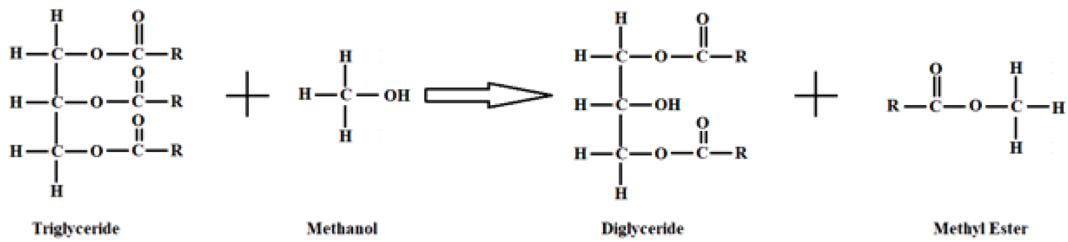
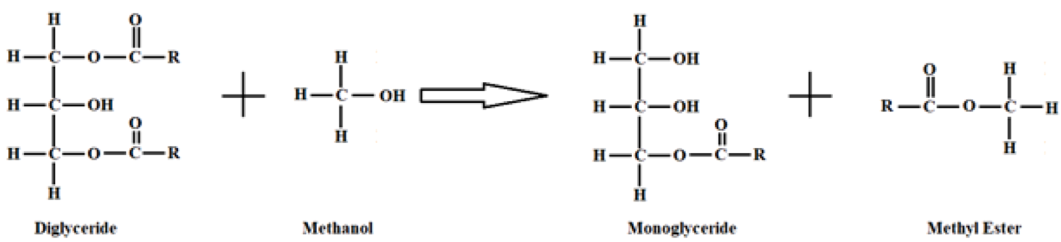


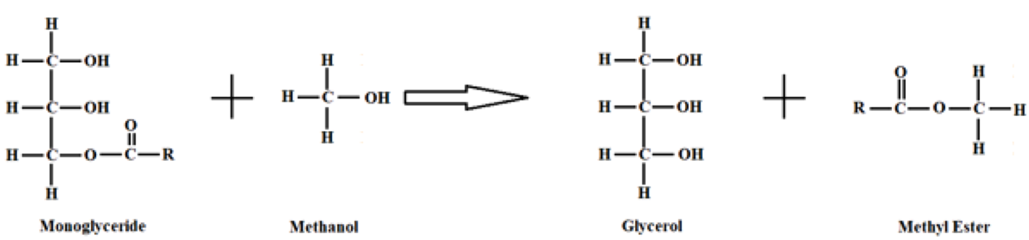
Fig. 5. Chemical reactions in the transesterification process.

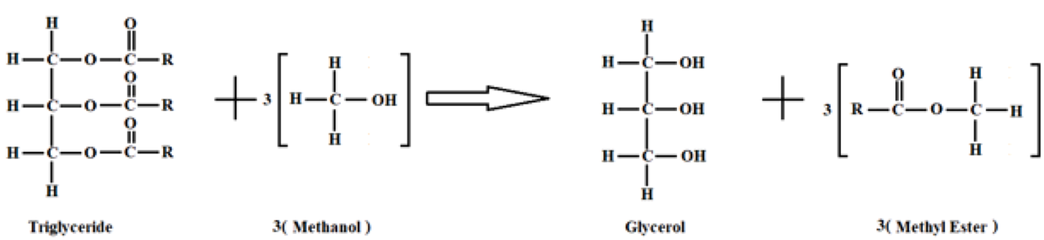
enzymatic (Lipases) [32]. The temperature should be below the boiling point of methanol, typically 60 °C, with one to two hours of reaction time and a 6:1 alcohol-to-oil molar ratio. This reaction produces diglycerides and methyl esters [33]. The ester bond in a triglyceride reacts with methanol to break one fatty acid chain, forming a diglyceride and a methyl ester, as illustrated in equation 1. Similarly, as depicted in equation 2, a diglyceride reacts with methanol, breaking another fatty acid chain and forming a monoglyceride and a methyl ester. Finally, a monoglyceride reacts with methanol to yield glycerol and methyl ester, as shown in equation 3. Moreover, equation 4 represents the overall reaction of biodiesel production from triglycerides.

molar ratios (around 10:1), elevated pressures (20–50 bar), and longer reaction times. After hydrolysis, glycerol and FFAs are separated and purified. The FFAs are then esterified with methanol, using acid catalysts like sulfuric acid, at temperatures of 60–70 °C, with an alcohol-to-FFA molar ratio of 6:1 and a catalyst concentration of 1–5 % by weight of FFAs [35]. This esterification reaction typically takes 1–2 h. The resulting mixture is allowed to settle, separating biodiesel (FAME) from water, followed by biodiesel purification. As illustrated in equation 5, a triglyceride reacts with water to form a diglyceride and a fatty acid. Similarly, a diglyceride reacts with water to produce a monoglyceride and a fatty acid, as shown in equation 6. Finally, a monoglyceride reacts with water to yield glycerol and a fatty acid, as depicted in equation 7.



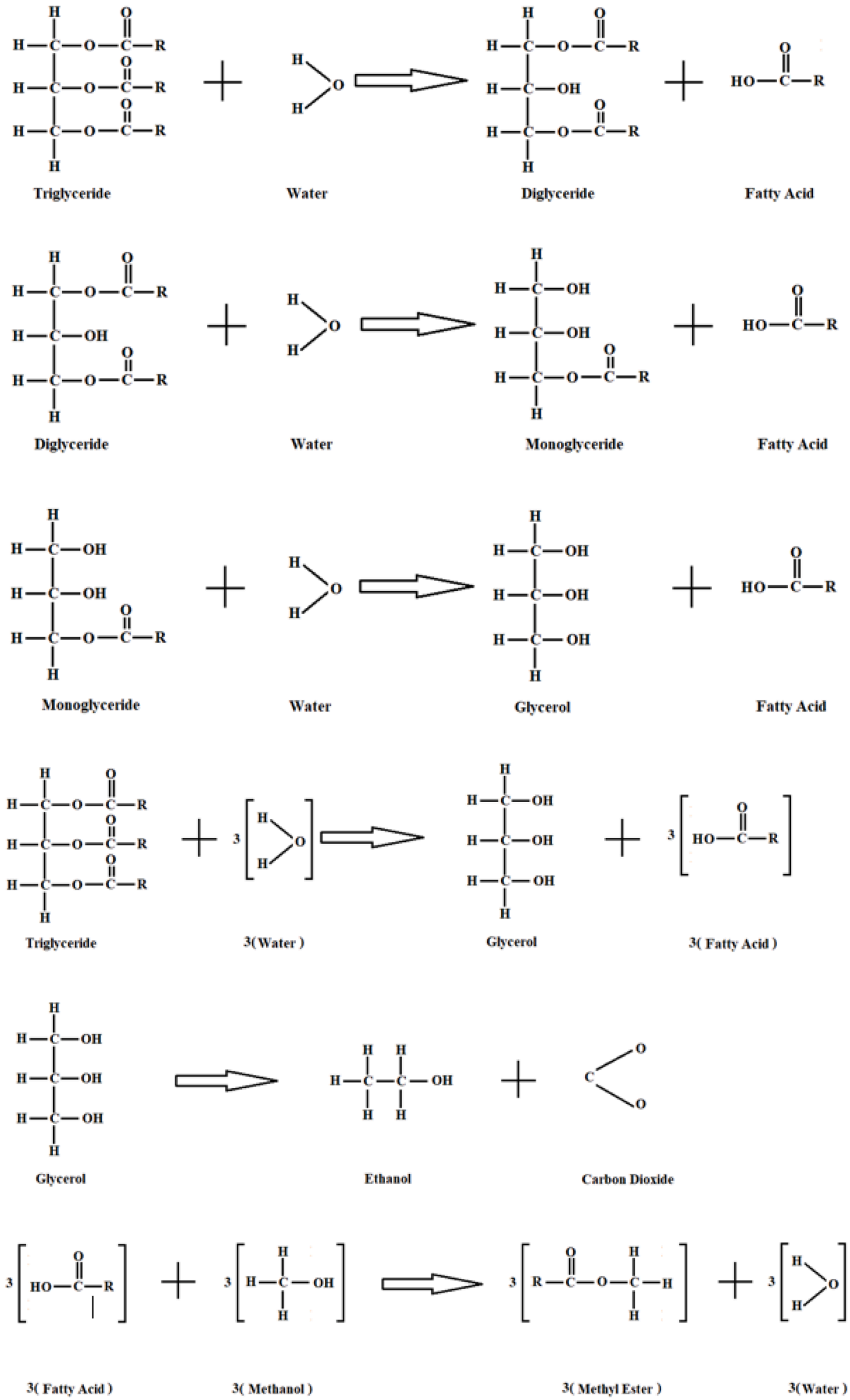






In a few cases, hydrolysis followed by esterification, converts triglyceride to glycerol. This is particularly used for feedstocks with high free fatty acids, such as waste oils and animal fats. In hydrolysis, triglycerides are broken down into glycerol and free fatty acids (FFAs) using water and catalysts like sulfuric acid or lipases [34]. This process typically requires higher temperatures i.e. 200–250 °C for non-enzymatic and 30–50 °C for enzymatic hydrolysis, high water-to-oil

Equation 8 shows that triglyceride reacts with three water molecules to yield glycerol and three fatty acid molecules. This glycerol undergoes fermentation to produce ethanol and carbon dioxide. Furthermore, the fatty acids react with methanol to form methyl esters and water, as demonstrated in equation 10. The overall reactions have been summarized in Eqs. (9 and 10).


Triglyceride
Water
Diglyceride
Fatty Acid
Diglyceride
Water
Monoglyceride
Fatty Acid
Monoglyceride
Water
Glycerol
Fatty Acid
Triglyceride
3(Water)
Glycerol
3(Fatty Acid)
Glycerol
Ethanol
Carbon Dioxide
3(Fatty Acid)
3(Methanol)
3(Methyl Ester)
3(Water)

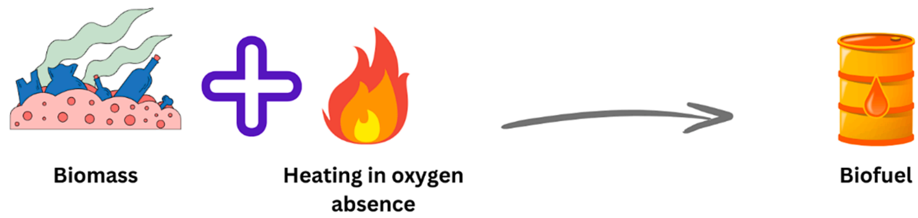


Fig. 6. The flow of the Pyrolysis Process.

Pyrolysis represents a versatile approach to converting a variety of waste sources into valuable products like bio-oil and syngas through high-temperature thermal decomposition in an oxygen-free environment [36]. The pyrolysis process is shown in Fig. 6. The catalysts involved in the pyrolysis process include zeolites, metal oxides, transition metals, alkaline earth metals, carbon-based catalysts [37]. This method efficiently handles mixed and complex wastes, making it suitable for the diverse compositions found in municipal and industrial waste streams. While consistently yielding energy-rich fuels from different waste types, pyrolysis necessitates substantial energy inputs and requires management of by-products such as char [38]. Variations in pyrolysis across waste sources primarily stem from distinct outputs and associated challenges. Agricultural waste, high in cellulose, often undergoes slow pyrolysis to optimize biochar production for soil enhancement alongside bio-oil and syngas generation [39]. Municipal waste, characterized by heterogeneity, typically undergoes fast pyrolysis for rapid conversion to bio-oil, necessitating thorough sorting and preprocessing [40]. Industrial waste, despite effective processing capabilities, entails high setup costs, operational expenses, and rigorous pollution controls, accommodating either pyrolysis method depending on product requirements [41]. Waste cooking oil, less commonly processed, yields a variety of products via fast pyrolysis [42]. Algae undergoes hydrothermal pyrolysis due to its high moisture content, converting wet biomass directly into valuable outputs [43]. These adaptations underscore the necessity of tailoring pyrolysis to suit each waste type's unique characteristics and desired outcomes.

Enzymatic processes offer environmentally friendly solutions for converting various waste sources into biofuels, characterized by mild reaction conditions and specificity toward target substrates. Across different waste types, such as agricultural, municipal, industrial, animal waste, waste cooking oil, and algae, enzymatic processes share similarities in their ability to selectively break down organic fractions [44]. They are particularly effective for lipid-rich materials like agricultural waste and algae, converting these into biodiesel with tailored enzymes designed for lipid extraction [45]. Enzymatic conversion of animal waste focuses on breaking down fats into biodiesel, although efficiency may vary depending on the protein content [46]. Algae, rich in lipids, undergoes enzymatic conversion to extract these oils, although the process faces challenges due to the high cost of enzymes specific to algal oils [47]. The scalability of converting various waste sources into biofuels hinges on feedstock availability and consistency, which are critical for reliable production scaling [48]. Technological readiness and efficiency in chemical (transesterification, pyrolysis) and enzymatic processes also influence scalability [48]. Adequate infrastructure for sorting and pre-treatment is vital, especially for diverse municipal and industrial wastes [49]. Economic factors, including enzyme costs and energy efficiency, significantly impact scalability [50]. Regulatory frameworks and environmental concerns further shape scalability, affecting waste management practices, emissions control, and compliance with sustainability standards during expansion [51]. Integrated solutions addressing these challenges across different waste streams are essential to achieve scalable biofuel production. Efficiency in converting diverse waste sources into biofuels hinges on several crucial factors. These include the inherent composition and characteristics of the waste materials, such as lipid content in agricultural and algal sources, and the complex organic fractions in municipal and industrial wastes [52]. The effectiveness and specificity of enzymes used in enzymatic processes are also pivotal, requiring tailored approaches for optimal conversion [44]. Factors like pre-treatment needs, especially for cellulose- or protein-rich wastes, and the availability of cost-effective processing technologies further influence efficiency [50]. Additionally, managing energy inputs for processes like pyrolysis, handling by-products, and adhering to environmental regulations for waste disposal and emissions control are critical determinants of overall efficiency in waste-to-biofuel conversion [52].

3.1. Biodiesel production from agricultural waste

Agricultural waste-based biomasses are composed of cellulose, starch, lignocellulose, lignin, hemicellulose, and oil [53]. Mainly the major crop residues that are utilized for bioethanol production include rice straw, wheat straw, and corn stover. These crops are available all year round. Sharma et al. [54] discussed the use of rice straw as feedstock to produce biofuel in reducing greenhouse gases. The major types of livestock wastes include manure and wastewater. Other than crop residues, wastes from fruits and vegetables, including unprocessed fruits and vegetables, are also a part of agricultural waste. Hence, the main composition of agricultural waste contains lignocellulosic composition, lipid content, proteins, carbohydrate-rich substrate, and moisture content. Feedstock rich in cellulose and hemicellulose content is favored for biodiesel production. Lignocellulosic biomasses, like straws and stoves, are high in cellulose. Conversely, manure has high moisture and organic content and a low C/N ratio, which is fermented more easily. Agricultural waste is utilized for biodiesel production through biochemical or biothermal conversion. Marzo et al. [55] used sugar beet roots as feedstock for ethanol fermentation. Converting agricultural waste into biofuel involves several critical processes characterized by specific chemical reactions. Initially, pretreatment includes mechanical, chemical, or thermal processes to prepare the waste, though no particular chemical reactions occur at this stage. During hydrolysis,

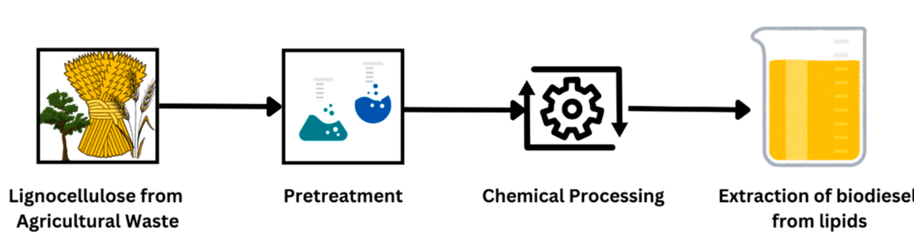


Fig. 7. Process of biodiesel production from agricultural waste.

polysaccharides are broken down into simple sugars through enzymatic or chemical hydrolysis [56,57]. In the fermentation stage, glucose undergoes alcoholic fermentation, producing ethanol and carbon dioxide [58–60]. Alternatively, anaerobic digestion through methanogenesis converts glucose into methane and carbon dioxide [61]. For biodiesel production, transesterification of lipids involves reacting triglycerides with methanol to yield methyl esters (biodiesel) and glycerol. The transesterification is the chemical reaction between triglycerides (ester) and alcohols (methanol and ethanol) to produce methyl or ethyl ester of long-chain fatty acids [62]. Triglycerides are the main components of fats and oils in agricultural feedstock. A catalyst is employed to facilitate the transesterification reaction. Regularly used catalysts include sodium hydroxide (NaOH) or potassium hydroxide (KOH) [63]. The transesterification reaction involves breaking ester bonds in triglycerides and the formation of new ester bonds with alcohol. The reaction occurs in the presence of the catalyst. The heterogeneous catalysts derived from agricultural wastes are many times used in the esterification method to synthesize fatty acid methyl ester (FAME) [64]. Gasification, a thermochemical process, converts carbon and water into carbon monoxide, hydrogen, and oxygen into carbon dioxide. Additionally, carbon monoxide reacts with water to produce carbon dioxide and hydrogen [65,66]. Finally, another thermochemical decomposition process, pyrolysis, breaks down biomass into bio-oil, syngas, and biochar. [67]. Fig. 7 shows the flow of events that take place to produce biodiesel from agricultural waste.

3.2. Biodiesel production from industrial waste

The waste collection and pretreatment involve identifying and characterizing industrial waste to understand its composition, chemical properties, and potential value. Different types of industrial waste may include byproducts, residues, or materials that can be repurposed. The conversion of industrial waste to biofuel involves several critical processes. Initially, pretreatment, which includes mechanical, chemical, or thermal processes, prepares the waste for further conversion, although no particular chemical reactions occur at this stage [68]. Cleaning, decontamination, or other processes are done to remove impurities or hazardous substances [69]. After removing large impurities, solids, and water from the waste oil through processes such as filtration or settling to improve the quality of the oil, chemical treatment is done [70]. During hydrolysis, polysaccharides are broken down into simple sugars through enzymatic or chemical hydrolysis, where complex carbohydrates are converted into glucose molecules. The chemical treatment processes may be employed to further purify the waste oil. This can include the use of chemicals to break down contaminants, separate water, or neutralize acidic components. Fractional distillation is a common method to separate different components in the waste oil based on their boiling points. This process helps remove impurities and separate the oil into fractions with specific properties [71].

In the fermentation stage, glucose undergoes alcoholic fermentation, producing ethanol and carbon dioxide. Alternatively, anaerobic digestion through methanogenesis converts glucose into methane and carbon dioxide. For biodiesel production, transesterification of lipids involves reacting triglycerides with methanol to yield methyl esters (biodiesel) and glycerol. Transesterification involves the setup of a reaction vessel or transesterification reactor. With oil having lower than 1 % free fatty acid content, single-stage transesterification can be performed [72]. This vessel is designed to handle the chemical reaction between feedstock (triglycerides) and alcohol. Next, alcohol (methanol or ethanol) is introduced into the reactor. The alcohol reacts with triglycerides in the feedstock to form biodiesel and glycerol. Then, add a catalyst to facilitate the transesterification reaction [26]. The common alkali-based catalysts include sodium hydroxide (NaOH) or potassium hydroxide (KOH) [73] while heterogeneous catalysts are also used [74] in some cases, the catalyst helps accelerate the reaction and is later separated from the final products. Gasification, a thermochemical process, converts carbon and water into carbon monoxide, hydrogen, carbon and oxygen into carbon dioxide. Additionally, carbon monoxide reacts with water to produce carbon dioxide and hydrogen. Finally, another thermochemical decomposition process, pyrolysis, breaks down biomass into bio-oil, syngas, and biochar. These processes collectively facilitate the transformation of industrial waste into various forms of biofuel. Hydro-treating involves the use of hydrogen under high pressure and temperature to remove sulfur, nitrogen, and other impurities from the waste oil. This process improves the quality of the oil and makes it suitable for further processing [75]. Cracking is a process that breaks down larger hydrocarbons in the waste oil into smaller, more valuable hydrocarbons. This can increase the yield of desirable products and improve the overall quality of the feedstock [76]. The complete process is illustrated in Fig. 8.

3.3. Biodiesel production from municipal waste

Municipal waste, also known as solid waste or garbage, is collected from households, businesses, and public spaces. This waste encompasses a wide variety of materials, including organic waste (such as food scraps and yard trimmings), paper, plastics, glass, metals, and other recyclables. Once collected, the waste undergoes sorting and separation at recycling facilities, as done by Woon et al. [77]. The manual and automated processes are used to separate different types of materials. One method used for separation is source separation [78]. The transfer stations and recycling centers also play a role in the separation of organic

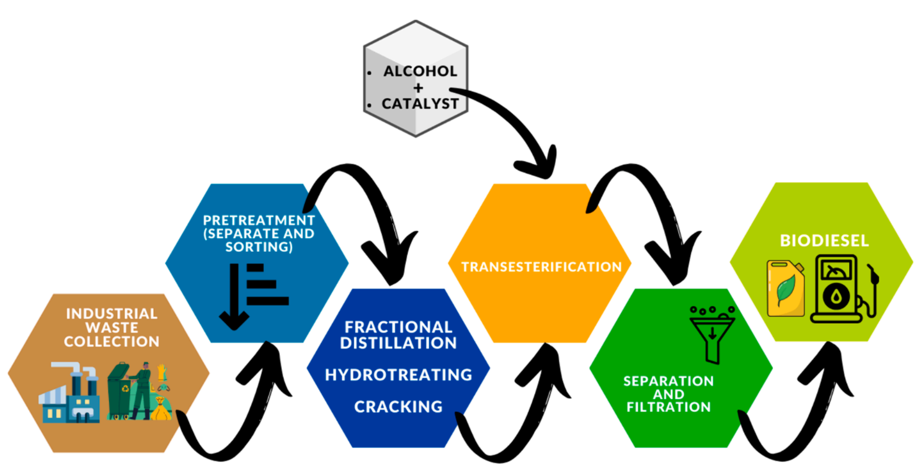


Fig. 8. Process of biodiesel production from industrial waste.

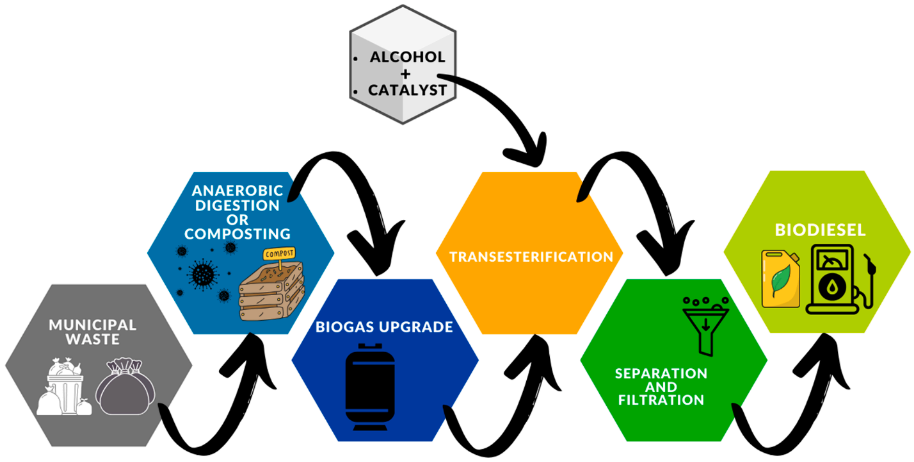


Fig. 9. Process of biodiesel production from municipal waste.

waste. Some advanced waste management facilities use automated sorting systems to separate different waste streams, including organics. These systems use technologies such as conveyor belts, sensors, and air classifiers to identify and divert organic materials for further processing. The pre-processing and feedstock preparation involves shredding, grinding, or chipping to reduce the particle size and increase the surface area for subsequent processing. Feedstock is prepared from this waste through anaerobic digestion or composting. In the anaerobic digestion process, microorganisms decompose organic materials in the absence of oxygen, yielding biogas (methane and carbon dioxide) and a nutrient-rich digestate [79]. In composting, organic waste undergoes controlled decomposition under aerobic conditions [80,81]. The remaining digestate from anaerobic digestion or the compost from composting is processed further. This may involve additional separation steps to remove contaminants or the extraction of valuable nutrients for reuse. It is ensured that the resulting feedstock meets the required standards. This includes monitoring factors such as moisture content, nutrient levels, and potential contaminants [82]. Biogas upgrading specifically focuses on the treatment of the gaseous byproduct produced during anaerobic digestion. The primary components of biogas are methane (CH_4) and carbon dioxide (CO_2), along with trace impurities. Biogas upgrading aims to increase the methane content, resulting in a purified gas known as biomethane or renewable natural gas (RNG) [83]. The transesterification process involves reacting triglycerides (fats and oils) with an alcohol (such as methanol or ethanol) in the presence of a catalyst to produce biodiesel (methyl or ethyl esters) and glycerol [84,85]. Choi et al. [86] used xylene as a solvent to separate water. Soxhlet extraction combined with alkaline transesterification has emerged as municipal waste's most widely applied biodiesel production line [87]. After transesterification, the biodiesel is separated from the glycerol byproduct. Furthermore, pyrolysis involves the thermal decomposition of organic materials in the absence of oxygen, resulting in products such as bio-oil [49,88,89]. Water in the sludge during transesterification can be separated using a solvent. Fig. 9 shows the biodiesel production process utilizing municipal wastes. The crude biodiesel undergoes further purification processes, including washing and drying, to meet quality standards for biodiesel.

3.4. Biodiesel production from waste cooking oil

Used cooking oil, fish waste, and bones are among the waste products that come from homes, restaurants, fishing boats, and processing facilities. These materials undergo initial sorting and preliminary treatment to eliminate impurities and undesirable particles specific to each type of waste. Subsequently, each type of waste undergoes tailored preparation procedures. Cooking oil waste undergoes filtration or settling processes to remove pollutants, debris, and water [90]. Meanwhile, methods like pressing, centrifugation, or rendering are employed to extract oil from fish waste and bones. The initial sorting considers the quality and composition of the WCO. This includes assessing its viscosity, fatty acid content, moisture content, and presence of impurities such as food particles, metals, or other contaminants. Sorting aims to segregate WCO into batches with similar characteristics to streamline pretreatment processes. Further refinement of this oil involves additional purification to eliminate contaminants and solid particles.

Transesterification is the chemical reaction with triglycerides (ester) and alcohols (methanol and ethanol) to manufacture methyl or ethyl ester of long-chain fatty acids [91]. Triglycerides are the main components of fats and oils in waste oil feedstocks. A catalyst is employed to facilitate the transesterification reaction. The most commonly used catalysts include sodium hydroxide (NaOH) or potassium hydroxide (KOH) [92]. The transesterification reaction involves breaking ester bonds in triglycerides and the formation of new ester bonds with alcohol. The reaction occurs in the presence of the catalyst. Pyrolysis is the method of thermally breaking down organic materials in an oxygen-free atmosphere to produce three unique phases: condensed liquids (bio-oil), gases (syngas), and solids (char). The biodiesel produced after transesterification is separated from the glycerol residue. After that, the raw biodiesel is subjected to additional refining processes, such as washing, drying, and in certain situations, extra refining steps. These

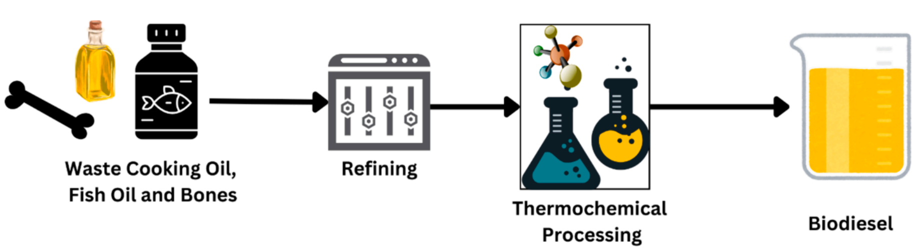


Fig. 10. Process of biodiesel production from waste cooking oil and fish bones.

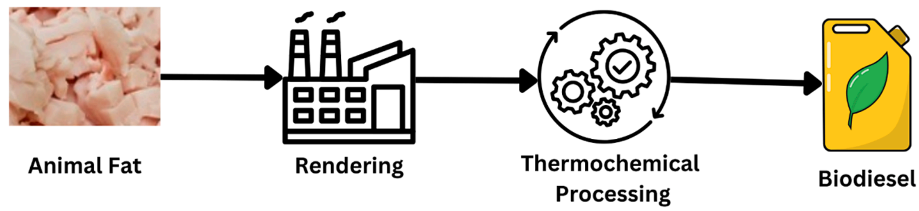


Fig. 11. Process of biodiesel production from animal fat.

procedures aim to eliminate any leftover pollutants or contaminants so that the biodiesel fulfills the necessary quality requirements. The yield rate of biodiesel depends on the concentration of free fatty acids and contaminants [93]. Enzymes are natural catalysts with eco-friendly operating conditions. Currently, researchers are investigating enzyme-mediated transesterification in order to overcome the drawbacks of chemical synthesis [94]. Weldeslase et al. [95] found that the average crystallite sizes of Zn-CaO and CaO nanoparticles that were calcined at 900 °C and then impregnated using a wet method were 21.14 nm and 12.51 nm, respectively, based on XRD patterns. With an optimal biodiesel yield of 96.65 % obtained at experimental conditions of 57.5 °C reaction temperature, 2 h of reaction time, 5 % (wt.) catalyst loading, and 14:1 methanol to oil molar ratio, the Zn-doped CaO thus proved excellent catalytic performance compared to pristine CaO. Fig. 10 explains the process of biodiesel production from waste cooking oil and fish bones.

3.5. Biodiesel production from waste animal fat

As a byproduct, waste animal fat is gathered from slaughterhouses, meat processing facilities, and the food industry. The tallow, grease, and other greasy leftovers from animal carcasses, trimmings, or processing waste are examples of this kind of fat. The first step in treating animal fat is to filter out contaminants, solids, and non-fat ingredients. This procedure may include boiling and filtering the fat to remove contaminants and clarify the oil. It is also possible to neutralize free fatty acids and eliminate undesirable impurities by treating them with acid or alkali. Triglycerides are the main elements of fats and oils in animal fat oils. A catalyst is employed to facilitate the transesterification reaction. Commonly used catalysts include sodium hydroxide (NaOH) or potassium hydroxide (KOH) [92]. The transesterification reaction involves breaking ester bonds in triglycerides and the formation of new ester bonds with alcohol. The reaction occurs in the presence of the catalyst. Although transesterification is more common, some of the researchers used the pyrolysis process. Pyrolysis is the method of thermally breaking down organic materials in an oxygen-free atmosphere to produce three unique phases: condensed liquids (bio-oil), gases (syngas), and solids (char). Research studies have carried out several trials to convert Waste Animal Fat (WAF) into bio-oil. The glycerol byproduct is separated from biodiesel. After that, the raw biodiesel is put through additional purification procedures, such as washing, drying, and occasionally more refining. These procedures seek to eliminate any leftover pollutants or impurities to ensure that the biodiesel meets quality requirements. Fig. 11 explains the biodiesel production process from animal fat.

Table 1
Algal species used for review.

Sr. No.	Species	Type
01	Chlorella vulgaris [102]	Microalgae
02	Spirulina [103]	Microalgae
03	Stoechospermum marginatum [104]	Macroalgae
04	Spirulina platensis [105]	Microalgae
05	Spirulina [136]	Microalgae
06	Euglena Sanguine [106]	Microalgae
07	Chlorella protothecoides [107]	Microalgae
08	Microalgae derived dioctyl phthalate [108]	Microalgae
09	Scenedesmus obliquus (S1) and Scenedesmus dimorphus (S2) [109]	Microalgae
10	Chlorella prothecoides [110]	Microalgae
11	Dunaliella tertiolecta [111]	Microalgae
12	Neochloris oleoabundans [112]	Microalgae

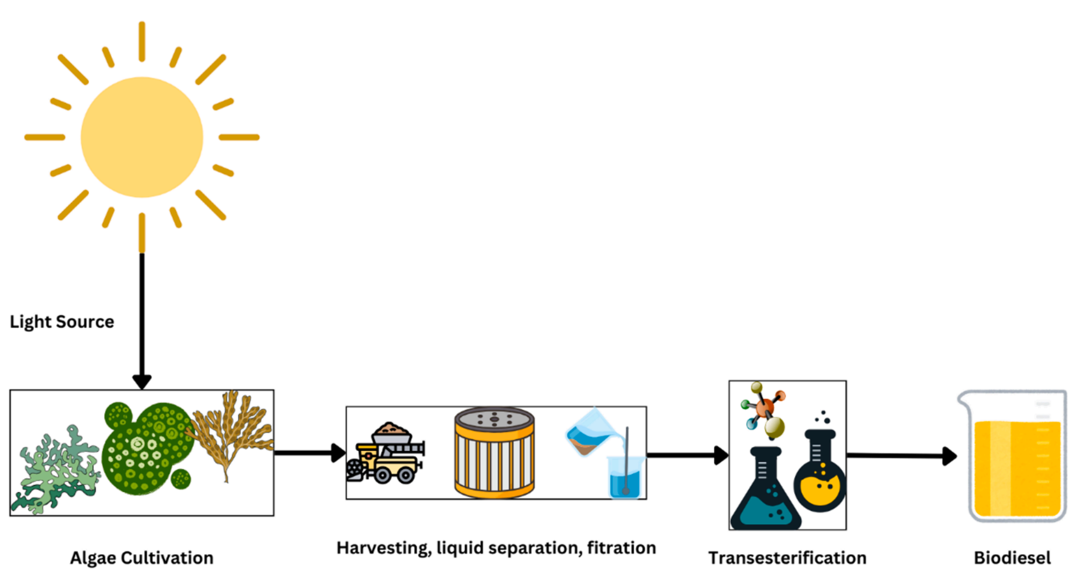


Fig. 12. Process of biodiesel production from algae [113].

Fig. 13. Environmental impacts of biodiesel and its alignment with sustainable development goals (SDGs).

3.6. Biodiesel production from algae

One of the many living organisms that serve as a valuable feedstock in the extraction of biofuels as a non-toxic substitute for fossil fuels is algae. With attributes like simple culture, significant biomass output, etc., algae appear to be among the best-suited organisms for the generation of biodiesel [96]. Algae can be divided into two main types: macroalgae and microalgae. Both macroalgae and microalgae have a tendency to produce diverse kinds of biofuels via distinct processes [97]. However, microalgae is the more favorable feedstock for biodiesel production due to its higher lipid content as compared to macroalgae [98]. Firstly algae are cultivated in carefully regulated settings, such as water bodies, containers, or specialized photobioreactors, where ideal growth parameters, like sunshine availability and rich in nutrients aquatic media, are carefully maintained. When the algae reach maturity, techniques like filtering, centrifugation, or flocculation are used as harvesting methods to extract the adult algae from their growing medium. The drying and preparatory steps involve carefully dehydrating the harvested algae biomass to remove any remaining moisture and get it ready for further processing. Then lipids are extracted from the biomass and subjected to a transesterification process with the interaction of methanol and H_2SO_4; then, this solution is left to settle into layers. The bottommost layer is glycerin, and the topmost layer is the produced biodiesel [99]. The pictorial representation of the biodiesel production process from algal waste is shown in Fig. 12. The species used for review are given in Table 1. Moreover, some species that have a very high potential for producing biodiesel but are researched very rarely are Chlamydomonas sp [100] and Asterarcys sp [101], etc.

4. Physicochemical properties

The physicochemical properties (Fig. 13) of biodiesel obtained from various waste sources are analyzed for its viscosity, cetane number, calorific value, density, flash point, pourpoint, etc. Table 2 displays the properties of the fuel blend. It is generally observed from existing research that the viscosity of the fuel blends from waste is slightly higher than conventional diesel at a given temperature. However, biodiesel from waste occasionally exhibits an improved cetane number. A high cetane number assists in quicker combustion [114]. This can result in increased fuel economy, fewer emissions, and better output. Similarly, the density of diesel is also comparable to the density of biodiesel derived from waste in most cases. The calorific value is slightly lower for fuel derived from waste than conventional diesel fuel. Refining waste fuel and further removing impurities from the fuel can help enhance the physiochemical properties of the fuel derived from waste. Kinematic viscosity (KV) is a relative ratio of fluid dynamic viscosity with density. The KV should be optimum as too much KV results in fuel injection issues and, ultimately, brake power decrease. The molecular breakdown results in declining kinematic viscosities [115]. The pour point indicates the temperature at which fuel solidifies and becomes too thick to pour. Essentially, it gauges the fuel's capacity to flow in colder conditions. A higher pour point indicates increased viscosity, making the fuel's flow harder at lower temperatures. This could lead to blockages in fuel lines and inadequate fuel delivery to the engine, resulting in challenges with starting and diminished engine performance during cold weather. The minimum temperature of the lubricant at which lubricant gives off enough vapors to produce an ignitable vapors blend is known as a flash point. FP shows the fire safety of lubricant oil application as it impacts its maximum functional limit. The malfunctioning in lubricant oil may happen in the case of lower FP [116]. Calorific value is a measure of the amount of energy released per unit mass or volume of a fuel during combustion. A fuel with a higher calorific value is capable of producing higher output power due to better combustion efficiency. The cetane rating of a fuel is a measure of its ignition quality or its ability to ignite

Table 2
Physicochemical properties of biodiesel derived from waste sources.

Source	Flash point (°C)	Pour point (°C)	KV (mm^2/s)	Density (kg/m^3)	Calorific value (MJ/kg)	Cetane rating
Agricultural Waste						
Rice husk [118]	>160	–	4.332	864	40.02	51.5
Oleander seed oil [119]	>200	–	46.58	898	125.37	63.55
Parseley oil [120]	127	−4.1	4.14		42.5	62.8
Sugarcane waste [121]	–	–	–	–	35.8	69.9
Rice bran [122]	–	–	5.8	890	39.94	39.9
Cotton seed [122]	–	–	5.4	875	40.2	40.02
Lemon grass waste [123]	150	–	4.18	984	36.27	38
Industrial Waste						
Waste cooking oil [124]	210	–	52.76	933	38.2	38
Waste tire oil [125]	–	–	2.64	820	42.9	54.8
Municipal Waste						
–	–	–	–	–	–	–
Waste cooking oil, Fish Oil and Bones						
Waste cotton seed oil [126]	110	1	4.5	870		
Fish oil (COD Liver Oil) [127]		−3		888		
WFO [128]	71	−2	4.12	892	7.956	51.2
Fish Oil [129]	80		3.56	848	41.29	52
Waste Palm oil [130]	63	8.2	5.1	877	41.41	48
Beef bone marrow [131]	161.5		9.809	882.9	40	57
Waste Cooking oil [132]	170		5.33	872		92.2
Pyrolysis of waste cooking oil [133]	28	−27	2.288	816.6	46.62	54.6
Transesterification of waste cooking oil [134]			3.93	881.4	39.45	58.88
Pyrolysis of waste cooking oil [135]	28	−27	2.288	816.6	46.62	54.6
Canola, safflower and waste oil mixture [136]	180		4.241	887.0	39.640	58
WCO biodiesel [137]	182			8790	38.15	56.7
Fish oil and waste palm cooking oil [138]	121	2	2.83	842.2	44.02	51
Waste Cooking Oil + Toluene [139]	89		6.3	850.3	41.6	43
Esterification of Plam Oil and Transesterification of Sunflower Oil [140]			2.65	822.9	44.07	
Pyrolysis of chicken slaughter waste, broiler excretes, and fish waste [141]	65		2.68	822	39.420	58
Waste Animal Fat						
Leather waste fat [142]	173.5	9	4.636	875.5		58.8
waste chicken fat [143]	170		4.11		40.20	56
Egyptian sheep fat oil [144]	70		2.5	828	41.8	51.5
Leather Fleshing and slaughterhouse wastes [145]	149	−3.27	4.82	887	37.3	66
Beef tallow oil [146]	90	2.2	3.61	774	41.10	57
Pyrolysis of waste animal fat [147]	50		4.01 m^2/sec	857	41.25	
Transesterification of animal fat oil [148]	64		5.0	882	39.4	52
Transesterification of beef fat oil [149]	64	6	5.0	882	39.4	52
Transesterification reaction of waste chicken fat [150]	150	−3	4.8	886	40.10	57.5
Algae						
Chlorella vulgaris [102]	124	−15	3.7	860	38.7	51.4
Microalgae Hydrothermal Liquifaction [151]	71.03		4.88	850		42.1
Spirulina microalgae [103]	86.4		3.26	836.5	42.2	48.88
Stoechospermum marginatum macroalgae species + Al_2O_3 [104]	82		3.0	985	45.52	53
Spirulina platensis [105]			5.66	860	41.36	
Spirulina [152]	53		0.002867 Pa s	842.7	43.76	52.335
Euglena Sanguine [106]	86.16	−3.77	3.24	840.78 g/cc	41.884	55.25
Algae [99]	71		4.27	853	39.67	46.5
S. marginatum macroalgae [153]	179	−4	4.7	830	43.665	54
Microalgae derived dioctyl phthalate [108]	94.2		7.608	867.44	50.32	47.12
Scenedesmus obliquus (S1) and Scenedesmus dimorphus(S2) [109]	73			817 gm / m^3	45.23	53.20
Heterotrophic chlorella prothecoides microalgae [110]	115		4.44	864	39.11	
Transesterification of Dunaliella tertiolecta bio-oil [111]	191		4.2	0.885	40.1	54
Transesterification of Neochloris oleoabundans oil [112]	148	−4	4.3	877	41.3	53

quickly after being injected into the combustion chamber of a diesel engine. Fuels with higher cetane ratings have shorter ignition delays, meaning they ignite more quickly after injection. This quick ignition is essential for smooth and efficient combustion. Fuels with higher cetane ratings tend to burn more completely, resulting in better fuel efficiency and reduced emissions [117]. Incomplete combustion can lead to higher levels of particulate matter and other pollutants.

5. Impact on engine performance

The impact of distinct biodiesel fuel blends derived from waste sources on engine performance is displayed in Table 3. The wastes are categorized into six categories: agricultural, industrial, municipal, cooking oil and fish oil, animal fats and algae. In the current study, agricultural wastes reviewed are cashew shells, cottonseed, jatropha seed, lemongrass, sugarcane, rice husk, rice bran, waste cooking oil, and waste animal fats. The results suggest an increase in BTE and combustion efficiency while a decrease in emissions with an increase in peak

Table 3
Impact of biodiesel on engine performance derived from different waste sources.

Reference	Operating Conditions	Engine Specification	Engine performance	Emissions	Combustion behavior
Waste cashew shell [164]	Engine operating at 1500 rpm	4.4 kW HCCI-DI engine	BTE↑	NOx↓ HC↓ CO↓	Peak pressure↑ Combustion duration↑
WCO [158]		Four-stroke turbo outboard motor	SFC↑	NOx↑ CO↓	
WCO [155]	The nano-additives at concentrations of 50 ppm and 100 ppm with the engine operating at 1500 rpm	4.4 kW HCCI-DI engine operating at 1500 rpm	BTE↑	NOx↑ HC↓ pm ↓ CO↓	
WCO [159]	Diesel engine operating at 1150, 1400, 1650, 1900 and 2150 rpm	Diesel engine	BSFC↑ BTE↑	NOx↑ HC↓ CO↓	
Waste chicken fat [165]	Engine speed of 2616.6 rpm			HC↓ CO↓ NOx↑	
WCO [160]	Silver nanoparticles (50 ppm) were constantly mixed with the various biodiesel blends		BSFC↑	CO↓	
WCO [154]	6:1 KOH was used at 1 % w/w of oil and was added to methanol for 1 h at 60 °C	Single-cylinder stationary engine		HC↓ CO↑ NOx↑	
WCO [125]	Engine run at 1600–3200 rpm oil temperature reached roughly 70 °C	Single-cylinder direct injection diesel engine	Torque ↓ BMEP↑ BTE ↑	CO_2↑ NOx↓	Effective pressure↑ Energy content ↑
WCO [162]	(CeO_2) cerium oxide and (MgO) magnesium oxide nano particles are blended with WCO B20CeO_2 (45 ppm) blend		BTE ↑ SFC↓	CO_2↓ NOx↓ HC ↓	
WCO [156]		A single-cylinder 4-stoke diesel engine	BTE↑ BSFC↑	NOx↑ HC↓ CO↓ PM↓	HRR↑ Effective pressure↑
Cotton seed oil [166]		A four-stroke, single cylinder, air-cooled, and direct-injection diesel engine connected to an electrical dynamometer	BTE↑	NOx↑ HC↓ CO↓	
Jatropha seeds oil [167]	Engine loads with 1500 rpm utilizing a four-stroke	Engine loads with 1500 rpm utilizing a four-stroke single-cylinder diesel engine		NOx↑ HC↓ CO↓	HRR↑ Cylinder pressure↑ ID↓
Lemongrass [123]		A four-stroke, water-cooled, naturally suctioned, unmodified single-cylinder engine	BTE↑ BSFC↓	NOx↓ CO↓ pm↑	
Microalgae [161]	Engine speed and compression ratio were fixed at 1500 rpm and 18:1 CR	Single-cylinder CI engine at 1500 rpm and 18:1 CR	BSFC↑ ITE↓	NOx↑ HC↓ CO↓	
Sugarcane bagasse/ rice husk [120]	Optimum variables were determined to be at 1458.60 rpm speed, 98.07 % load, and B20SNP100		BSFC↓ BSEC↓ BTE↑	NOx↑ HC↓ CO↓	
Rice bran oil [168]	17:5:1 (CR) at a stable speed of about 1500 rpm	Diesel engine of a compression ratio 17:5:1 (CR)	BTE↑	NOx↓ HC↓ CO↓	Exhaust temperature↑
Sugarcane [157]		Medium-sized diesel engine under Proconve P7 standard		NOx↓ CO↓ pm↓	
Sugarcane [121]		Modern medium-duty diesel engine		NOx↑ HC↓ CO↓	
Cashew nut shell oil [169]	4.4 kW @ 1500 rpm	RCCI engines with 110 mm stroke, 87.5 mm bore, and 17.5:1 compression ratio	BTE↑ Combustion efficiency ↑	NOx↓ HC↓ CO↓	Peak pressure ↑
Dairy milk waste [170]		Direct injection dual-cylinder diesel engine	BSFC ↑	NOx↑	
Rice brown oil [122]	Diesel engine with rated power of 3.5 kW and speed 1500 rpm	Single-cylinder, four-stroke diesel engine with a rated power of 3.5 kW and speed of 1500 rpm	BP↓ BTE↓ BSFC↑	NOx↑ CO_2↑ HC↓ CO↓	
Cottonseed oil [122]	Rated power of 3.5 kW and speed of 1500 rpm	Single cylinder, four-stroke diesel engine with a rated power of 3.5 kW and speed of 1500 rpm	BP↑ BTE↓ Fuel consumption↓	NOx↑ HC↓ CO↓	
Fish oil [171]		Single-cylinder, direct-injection diesel engine	BTE↓	SO_2↓	
Animal fat [172]		A single cylinder four stroke diesel engine		NOx↓ HC↓	Peak pressure↑ HRR↓

(continued on next page)

Table 3 (*continued*)

Reference	Operating Conditions	Engine Specification	Engine performance	Emissions	Combustion behavior
				CO↓ PM↑	
Chicken fat [173]		A small single cylinder, four-stroke, air-cooled, combustion ignition engine	BTE↑ EGT↑ HRR↑	NOx↑ HC↓ CO↓ PM↓	
Cotton Seed Oil [126]	Experiments were conducted at varying loads, variable compression ratio and constant speed of 1500 rpm	4 Stroke, single-cylinder, water-cooled, with variable compression ratio	BTE↑ BSEC↓	CO ↓ HC ↓ NO_X except B40 ↓	
Waste Cooking Oil [128]	A fixed 1800 rpm at full load condition	Single Cylinder Diesel Engine	Torque ↓ Engine BP ↓ BSFC↑	CO ↓ HC unburnt ↓ NO_X ↓	
Fish Oil [129]	1400 rpm with varying loads	A single-cylinder common rail diesel engine	Engine Power ↓ BSFC↑	CO ↓ HC ↓ Soot Emissions ↓ NO_X ↑	
Waste Palm Oil [130]	A constant speed with variable loads	A four-stroke, single cylinder direct injection	BTE↑ BSEC ↓	CO ↓ HC ↓ CO_2 ↓ NO_X↑	
Beef Bone Marrow [131]	A constant speed of 1500 rpm with varying load	Four-cylinder, water-cooled, four-strokes, and a direct-injection diesel engine	SFC↑ Thermal Efficiency ↓ EGT↑	CO_2 ↑ CO ↓ NO_X ↓ HC ↓	
Waste Cooking Oil [132]	Varying speeds and loads	Cummins four-cylinder common rail fuel, diesel engine		HC ↓ CO ↓ NO_X ↑	
Waste Cooking Oil [133]	A constant speed of 1500 rpm and varying load	A single cylinder, four strokes, air-cooled, direct-injection diesel engine	BSFC ↑ BTE ↓	NO_X ↓ CO ↓ HC ↑	Ignition delay ↓ Peak Pressure ↓ HRR ↓
Waste Cooking Oil [134]	A constant speed of 3000 rpm and varying load	A single-cylinder, four-stroke, naturally aspirated and direct injection diesel engine	BSEC ↑ BSFC ↑ EGT ↓	CO ↓ NOx ↓ Smoke Opacity ↓	
Waste Cooking Oil [135]	A constant speed of 1500 rpm and varying load	A single cylinder, Direct-injection diesel engine	TE ↓ SFC ↑	CO ↓ NOx ↓ HC ↑ Smoke Emissions ↑	
Waste Cooking Oil [136]	A constant speed of 3000 rpm and varying load	A naturally aspirated, air-cooled, single-cylinder, four-stroke, direct-injection diesel engine	BTE ↓ BSFC ↑	CO ↓ HC ↓ Smoke Emissions ↓ NOx ↑ CO_2 ↑	
Waste Cooking Oil [137]	A constant speed of 3000 rpm and full load	A single-cylinder, dual fuel, compression ignition engine, a water-cooled, naturally aspirated, four-stroke	BSFC ↑ BTE ↓	CO ↓ NOx ↑ HC ↓	Ignition Delay ↓ Peak Pressure ↓
Fish Oil and Waste Cooking Oil [138]		A single-cylinder, four-stroke, direct-injection diesel engine	SFC ↑ TE ↓	CO ↓ HC ↓ Smoke ↓ NOx ↑	
Waste Cooking Oil [139]	A constant engine speed of 1800 rpm and varying power	A single-cylinder, direct injection, air-cooled, diesel engine	BTE ↑ BSFC ↓ EGT ↑	CO ↓ NOx ↓ Smoke Emission ↓	In-Cylinder Pressure ↓ HRR ↑
Palm Oil and Sunflower Oil [140]	Variable speed (3200—4000 rpm)	Single Cylinder, diesel engine, four strokes, and naturally aspirated	BSFC ↑ BTE ↑	NOx ↓ Smoke Opacity ↓ HC ↓ CO_2 ↓ CO ↓	
Slaughter Waste, Fish Waste [141]	A constant speed of 1500 rpm and varying load	Four-stroke, Single-cylinder, diesel engine		CO ↓ HC ↓ NOx ↓ CO_2 ↑	
Sheep Fat Oil [144]	1500 rpm fixed with varying loads	A single cylinder, four-stroke, air-cooled	BSFC ↑	CO ↓ HC ↓ Smoke ↓ NO_X ↑	

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Table 3 (*continued*)

Reference	Operating Conditions	Engine Specification	Engine performance	Emissions	Combustion behavior
Leather Fleshings [145]	1500 rpm	A four-stroke, single cylinder water cooled	SFC ↑ BTE ↓	CO_2 ↑ CO ↓ NO_X ↑	
Beef Tallow Oil [146]	A constant speed of 1500 rpm with varying load	A water-cooled, single cylinder, direct-injection diesel engine	BSFC 2 % than B20 ↓ BTE ↑	CO ↑ NO_X ↓	
Waste Animal Fat [147]	Variable speed 800 – 1500 rpm	Water-cooled, four-stroke, Indirect injection (IDI), naturally aspirated diesel engine		CO ↓ HC ↓ CO_2 ↓ NOx ↑	Peak Pressure ↑ HRR ↓
Animal Fat [148]	1500 rpm	Single cylinder four-stroke compression ignition engine	BSFC ↑ BTE ↓	CO ↑ UHC ↓ NOx ↑ Smoke ↑	HRR ↓
Beef Fat Oil [149]	1500 rpm	A single cylinder four stroke diesel engine	BTE ↓ Fuel Consumption ↑	CO ↓ UHC ↓ NOx ↓ Smoke ↑	Cylinder Pressure ↑ HRR ↓
Waste Chicken Fat [150]	A constant speed of 1500 rpm and varying load	A single-cylinder, direct-injection diesel engine	BSFC ↑ BTE ↓ EGT ↓	CO ↓ HC ↓ Smoke Emission ↓ NOx ↑	
Chlorella vulgaris [102]	Full load, variable speed from 2000 – 3000 rpm	A single-cylinder, four-stroke, direct injection, diesel engine	BSFC ↑ EGT ↓	CO ↓ CO_2 ↓ HC ↓ NO_X ↑	
Microalgae [151]	A constant speed of 1500 rpm with variable load	6-cylinder common rail direct injection (DI) diesel engine	BTE ↓ BSFC ↑ BMEP ↓	CO ↓ PM ↑ NO_X ↓	Ignition Lag ↑ Peak Pressure ↓ Pressure Rise ↑ (BMEP)
Spirulina microalgae [103]	A constant speed of 1500 rpm with variable load	Naturally aspirated diesel engine	EGT ↓ SFC ↑ BTE ↓	NO_X ↓ BSN ↓ PM ↓	CPP ↓ IDP ↑
Stoechospermum marginatum macroalgae species + Al_2O_3 [104]	A constant speed of 1500 rpm with variable load	Four-stroke single-cylinder diesel engine		HC ↓ CO ↓ NO_X ↑ Smoke ↓	
Spirulina platensis [105]	A constant speed of 1500 rpm with variable load	Four-stroke single-cylinder naturally aspirated. diesel engine	BTE ↓	HC ↓ CO ↓ Smoke ↓ NOx ↑	In-Cylinder Temperature ↑ Max. Pressure Rise ↓
Spirulina [152]	Variable loads and compression ratios	A single-cylinder, 4-stroke diesel engine	BSFC ↑ BTE ↓ EGT ↓	CO_2 ↑ CO ↓ NO_X ↑ HC ↓	
Euglena Sanguine [106]	1500 rpm, variable load	A single-cylinder, four strokes, water-cooled	BSFC ↑ BTE ↓ EGT ↑	CO ↓ NO_X ↑ HC ↓	Smoke Opacity ↓
Algae [99]	1500 rpm, variable load	A single-cylinder compression ignition VCR engine	BSFC ↓ BTE ↑ EGT ↑	CO ↓ HC ↓	
S. marginatum macroalgae [153]	1500 rpm, variable load	A single-cylinder compression-ignition engine	BSFC ↓ BTE ↑ EGT ↑		
Chlorella protothecoides [107]	1500 rpm	four-stroke, single-cylinder, direct injection, and water-cooled diesel engine	SFC ↑ BTE ↓ Peak Torque ↓ EGT ↓	NOx ↑ COx ↑ Smoke ↓	Peak cylinder pressure ↓ Cylinder temperature↓
Microalgae derived dioctyl phthalate [108]	1500 rpm	6-cylinder, inline common rail injection, turbocharged diesel engine	ITE ↑ BSFC ↑		IMEP ↓ BMEP ↓ Blowby ↓
Scenedesmus obliquus (S1) and Scenedesmus dimorphus(S2) [109]	Three different engine speeds at 2500, 2000 and 1500 rpm	Air-cooled DI diesel engine with a compression ratio of 18:1	Torque ↓ BTE ↑ BSFC ↑	NOx ↓ CO_2 ↓ Smoke Emission ↓ HC ↑	
Chlorella prothecoides [110]		Single-cylinder, 4-stroke, water-cooled, stationary Kirloskar DI diesel engine	Torque ↓ Brake Power ↓ BTE ↓ BSFC ↑	CO ↓ CO_2 ↓ NOx ↓ O_2 ↑	
Dunaliella tertiolecta [111]	2020 rpm	A single-cylinder horizontal four-time CI engine with air-cool	Power Output ↓ BSFC ↓	CO ↓ CO_2 ↓ NOx ↑	

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Table 3 (*continued*)

Reference	Operating Conditions	Engine Specification	Engine performance	Emissions	Combustion behavior
Neochloris oleoabundans [112]	1500 rpm, variable load	Single cylinder 4-stroke diesel engine	BTE ↓ BSFC ↑	SOx ↓ HC ↓ CO ↓ NOx ↑ HC ↓ Smoke ↓	Peak Pressure ↓ HRR↓ ID↓

pressure in the case of cashew shells. This decrease in emissions might be due to the addition of nanoparticles. In the case of cottonseed oil, fuel consumption decreases, BTE increases, and emissions decrease except NOx. NOx increase is due to the high combustion temperature and high unsaturated fatty acids [122]. The same emission trends are with jatropha seed oil and sugarcane. With rice bran, BTE increases, and emissions (NOx, HC, CO) are decreased with high exhaust temperatures. For waste cooking oil, the performance parameters (BTE, BSFC, and EGT) increase while torque decreases, and in the case of emissions HC, CO, CO_2, and Smoke Opacity decrease while NOx emissions, cylinder pressure and heat release rate increase, but there are some anomalies where an increase in CO_2, HC and smoke but a decrease in NOx was observed. When fish oil is used, there is a decrease in EGT and power while there is an increase in BSFC, with emissions showing a similar trend to waste cooking oil increase in NOx with a decrease in other emissions.

In the case of bone marrow, the thermal efficiency decreases while BSFC and EGT increase and in emissions, there is an increase in CO_2 with a decrease in NOx, CO and HC. Similar to waste cooking oil, there is an increase in BSFC and a decrease in BTE while emissions (HC, CO, Smoke) show a declining trend and the increasing trend is observed in NOx emissions with the use of animal fats like chicken and sheep fat oils. Moreover, when beef fat is used, NOx decreases with the increase in smoke. The microalgae species reviewed are Chlorella vulgaris, spirulina, Spirulina platensis, Euglena Sanguine, chlorella protothecoides, Scenedesmus obliquus, Scenedesmus dimorphus, Dunaliella tertiolecta and Neochloris oleoabundans while macroalgae species reviewed are: Stoechospermum marginatum macroalgae. Microalgae shows varying trends, with an increase in BSFC and a decrease in EGT and BTE in some cases, while in other cases, EGT and BTE increase and BSFC decreases; in terms of performance parameters, a decrease in torque and power output is observed. Moreover, it also shows the varying trends for emission parameters; in some cases, NOx increases, while in other cases, NOx shows a decreasing trend. The increase in NOx is because of the higher oxygen content and improvement in the timing of injection and combustion temperature [102]. But on the other hand, CO_2, CO, and HC decreases in almost all cases except one or two. The increase in CO_2 is due to the presence of a higher oxygen amount, which reacts with CO to produce CO_2 [152]. In macroalgae, there is an increase in BSFC and a decrease in BTE and EGT. The emission trends are the same as sheep fat oils, a decrease in CO, HC and smoke while an increase in NOx.

The majority of biofuels, including Waste Cashew Shell, Cotton Seed Oil, Jatropha Seeds Oil, Lemongrass, Animal Fat, Chicken Fat, etc., show decreased CO emissions. This suggests more complete combustion with these biofuels, possibly due to the oxygen content in the biofuels aiding the oxidation process. Only three cases, one of WCO [154] and the other of Beef Tallow [91] and Animal Fat [93], displayed an increase in CO emissions, potentially due to incomplete combustion or suboptimal engine conditions. Similarly, most biofuels show reduced hydrocarbon emissions, including Waste Cashew Shell, WCO, Cotton Seed Oil, Jatropha seed oil, Lemongrass, Animal Fat, Chicken Fat, etc. The oxygen content in biofuels promotes more complete combustion, reducing unburned hydrocarbons. Only certain specific cases like WCO [133,135] and a case of algae of the Scenedesmus genus [109] showed an increase in HC emissions, which could be attributed to less efficient combustion or differences in fuel properties. Moreover, NOx emissions displayed a mixed trend. In many studies use of WCO, Waste Cashew Shell, Cotton Seed Oil, Lemongrass, Sugarcane Bagasse/Rice Husk, Cashew Nut Shell Oil, Dairy Milk Waste, Rice Bran Oil, Sugarcane, Fish Oil, Palm Oil and Sunflower Oil, Leather Fleshings, Beef Tallow Oil, and Beef Fat Oil showed a reduced NOx emission These reductions may be due to lower peak combustion temperatures or the presence of oxygenated compounds in the biofuels that help lower NOx formation. On the contrary, many studies also revealed that WCO, Cottonseed Oil, Jatropha Seeds Oil, Animal Fat, Microalgae, Chicken Fat, Spirulina and Chlorella vulgaris showed increased NOx emissions. This is likely due to the higher combustion temperatures associated with these biofuels, which promote the formation of nitrogen oxides. Several biofuels, like WCO [155,156], sugarcane [157] and specific microalgae oils [103], show reduced particulate matter emissions, likely due to better combustion characteristics and oxygenated compounds in biofuels. However, very few biofuels, like those derived from specific microalgae species [151] and lemongrass [76] increase PM emissions under certain conditions.

Most biofuels like Waste Cashew Shell, WCO, Cashew Nut Shell Oil, Cotton Seed Oil, Jatropha Seeds Oil, Lemongrass, Sugarcane Bagasse/Rice Husk, and Cottonseed Oil show an increase in BTE. This suggests that these fuels can provide better energy conversion efficiency compared to conventional diesel, possibly due to improved combustion efficiency and higher calorific values. However, a few biofuels like WCO [136 137], Leather Fleshings [145], Animal Fat [148–150] and Microalgae [151 105 152 106 110 112 107] show a decrease in BTE, indicating less efficient energy conversion. One of the possible reasons could be the lower energy content in the biofuels or suboptimal combustion characteristics. Hence, biofuels can either improve or reduce BTE depending on their properties and the engine setup. Generally, biofuels with better combustion efficiency and higher calorific value show increased BTE. Furthermore, SFC tends to increase with biofuels, indicating that more fuel is often needed for the same energy output, though some biofuels with better combustion characteristics can reduce SFC. Many biofuels, especially WCO [158 159 160 128 133 134 136], fish oil [129 138] and some cases of animal fat oil [148 150 144], Microalgae [102,151 103 152 106 108 110 112 107 109 161], Leather Fleshings [145] and others show an increased SFC. This indicates that more fuel is required to produce the same amount of energy, possibly due to lower calorific value or less efficient combustion characteristics. However, certain biofuels like lemongrass [123], WCO [162], Sugarcane Bagasse/Rice Husk [120], and some microalgae blend [99 153 111] show decreased SFC, indicating improved fuel efficiency. This could be attributed to better combustion efficiency and higher energy content in these biofuels.

In summary, it is noted that for most fuel blends derived from wastes, carbon monoxide emission, carbon dioxide, and hydrocarbon emission decreased. In most cases, nitrogen oxide emission showed an increase, and for some cases, it also reduced. The NOx emissions are regulated to meet a minimum benchmark, as they are responsible for the greenhouse effect, respiratory diseases and many other environmental issues [163]. In many cases, particulate matter also decreased. Furthermore, it is noted that the engine performance showed increasing values for brake thermal efficiency (BTE). In many cases, BTE increased, while a few studies also showed a decreasing trend of BTE. Furthermore, the BSFC also increased overall for fuel derived from waste. Moreover, BSFC showed a varying trend with an increase in some cases while also

Table 4
Advantages and disadvantages of biodiesel by waste sources.

Waste Material	Advantages	Disadvantages
Municipal Waste	• Renewable and sustainable from organic waste [77] Waste reduction and alleviates the burden on landfill [15] Reduced greenhouse gas emissions [81] Lubricating properties reducing engine wear and life [84,89] Compatibility with existing infrastructure [86]	• Feedstock composition variability makes consistent feedstock challenging [49] Poor cold weather performance in certain climates [52] High production costs [87] Glycerol by-product, which requires proper disposal or utilization [83]
Agricultural Waste	• Renewable sources from renewable crops [174] Reduced emissions like low Sulphur [65] Environmental benefits aligned with sustainable goals [175]	• Uncertain quantity and yield [176] Technology development cost [52] Cold weather operation considerations due to higher cloud points [52] Storage stability as biodiesel may degrade over time [60] Feedstock availability due to dependence on crops [176]
Industrial Waste	• Environmental sustainability [72] Waste utilization by repurposing industrial waste [76] Biodegradability [76] Job creation [26] Energy security reduced reliance on imported fossil fuel [72]	• Land use and competition [177] Resource intensity as may require water, energy, and agricultural inputs [52] Engine compatibility, as engine modifications may be required [26] Land use change may result in habitat loss [6] Glycerol by-product has to be managed [176]
Waste Cooking Oil, Fish Oil and Bones	• Resource optimization reduces the demand for fresh raw material [77] Environmental impact reduction [73] Cost effectiveness than virgin oils and fossil fuels [178] Steady and dependable waste supply for biodiesel [179]	• Variability in waste makeup affecting consistency and dependability [51] Extraction complexity [52] Consumer acceptance [7]
Waste Animal Fats	• Efficient resource utilization and consistent with sustainable methods [180] Environmental impact reduction [154] Cost-effectiveness [26]	• Variability in fat composition can impact consistency and dependability [176] Extraction complexity due to waste management and production requirements [51] Consumer acceptance [7]
Algae	• Lower environmental impact and few carbon emissions [181] Higher oil yield potential than conventional oilseed crops [69] Less threat to food crops as can be grown in varying conditions [182]	• High operational costs due to technique and infrastructure requirements [6] Technological challenges [69] Growing algae may demand a lot of water, land and nutrients [183] Energy-intensive and time-consuming oil extraction may reduce overall efficiency [110]

showing a decreasing trend in many cases. Overall, the combustion behavior showed increased peak pressure and combustion duration. For instance, the NOx emission was increased in the case of WCO [111–113] but decreased in the case of nanoparticles in WCO [162]. A similar trend was observed for algae-based biodiesel, with a decrease in CO and PM.

6. Advantages and disadvantages

Table 4 outlines the advantages and disadvantages of various waste materials used for biodiesel production, highlighting their potential for renewable energy and environmental benefits. Municipal waste, agricultural waste, industrial waste, waste cooking oil, fish oil and bones, waste animal fats, and algae all offer unique benefits such as reduced greenhouse gas emissions, cost-effectiveness, and environmental sustainability. These materials can alleviate landfill burdens, provide consistent waste supplies, and contribute to energy security.

However, challenges such as feedstock composition variability, high production and development costs, technological complexities, and issues related to cold weather performance and storage stability must be addressed. Additionally, concerns around consumer acceptance, resource intensity, and competition with land use pose significant hurdles. Managing by-products like glycerol and ensuring compatibility with existing infrastructure are also critical for the successful integration of these waste materials into biodiesel production.

7. Applications

Bioethanol has risen as a prominent energy source in recent years, particularly in Brazil and the United States. Together, these two countries dominated the global bioethanol production landscape in 2011, contributing a staggering 87.1 % of the total output [184]. Moreover, biodiesel offers a versatile solution for heating applications, as it can be seamlessly blended with traditional petroleum-based heating oil in different ratios. This blended fuel is then utilized to heat residential and commercial boilers efficiently. Neste Oil asserts that its EN-590 diesel surpasses both conventional diesel and other biodiesel alternatives available in the market, setting a new standard for performance and efficiency [185]. Furthermore, the Volkswagen Group has announced that numerous vehicles in its lineup are designed to run smoothly on biodiesel blends ranging from B5 to B100, derived from rapeseed oil while meeting the stringent EN 14214 standard [186]. Biogas is also used as a source to produce electricity. China stands at the forefront of global biogas production, generating an impressive 3.8 TWh of electricity annually. Following closely, the United States secures the second position, producing 0.224 TWh of electricity each year [187]. Biofuels have been used in jet engines. The inaugurated test flight using blended biofuel took place in 2008, and in 2011, blended fuels with 50 % biofuels were allowed on commercial flights. In 2023 SAF production reached 600 million liters, representing 0.2 % of global jet fuel use [188]. Also, beginning in 2020, Qantas announced its intention to adopt a 50/50 blend of SG Preston's biofuel for its Los Angeles-Australia flights. Concurrently, SG Preston also entered into a decade-long agreement to supply fuel to JetBlue Airways. Meanwhile, Neste outlined ambitious plans to bolster its renewable fuel production capacity across multiple sites. By 2020, it aimed to elevate its output from 2.7 to 3.0 million tons annually, with further expansions slated for its Singapore facilities, envisaging an investment of €1.4 billion ($1.6 billion) to enhance capacity to 4.5 million tons by 2022 [189]. Moreover, biochar has also been used to improve crop yield. In Oregon's dryland wheat cropping systems, the application of biochar at a rate of 10 tons per acre has demonstrated remarkable results. Notably, it led to an elevation in soil pH levels and triggered a substantial surge in crop yield, nearing an impressive 30 % increase. Furthermore, biochar exhibits promising attributes in greenhouse environments as a viable alternative to conventional substrates like perlite and peat moss. Beyond its role as a replacement, biochar plays an essential function in curbing nutrient leaching, showcasing an 11 % reduction compared to traditional growing media. These findings underscore the multifaceted benefits of biochar utilization, both in enhancing agricultural productivity and promoting sustainability in horticultural practices [190].

8. Challenges and recent advancements

8.1. Municipal waste

The production of biodiesel from municipal waste presents a set of notable challenges that require concerted efforts from researchers and industry players. A primary challenge stems from the inherent variability of municipal waste, with diverse compositions complicating the task of maintaining consistent feedstock quality for biodiesel production. Contaminants and impurities found in municipal waste, such as heavy metals, pose additional challenges by potentially affecting the catalysts integral to the biodiesel production process [191]. Extracting usable oils or fats from the complex feedstock is also challenging, demanding cost-effective and efficient conversion methods. Cold weather performance represents another hurdle, as biodiesel derived from certain feedstocks may exhibit poor cold flow properties, impacting its efficacy in colder climates. Technological challenges abound, encompassing the development of scalable and cost-effective production technologies, optimization of reaction kinetics, and ensuring overall process efficiency. Achieving economic viability is crucial, given that production costs of biodiesel from municipal waste may exceed those of traditional fossil fuels. Glycerol, a byproduct of biodiesel production, requires careful management for proper disposal or utilization in an environmentally friendly manner. Infrastructure compatibility and potential land use concerns also figure prominently, with the need for engine modifications and considerations about competing land use. Regulatory compliance, encompassing environmental standards and waste management regulations, adds another layer of complexity. Public perception and acceptance of reusing municipal waste play a pivotal role, necessitating efforts to address concerns and raise awareness about biodiesel's environmental and economic benefits from municipal waste. Overcoming these challenges demands collaborative initiatives, technological advancements, and supportive policy frameworks to foster the sustainable production of biodiesel from municipal waste.

Diversifying feedstock is a crucial aspect of advancing municipal waste biodiesel production. By exploring various waste streams, such as food waste, algae, and wastewater sludge, researchers aim to optimize the efficiency of biodiesel production processes. Catalyst development also received attention, aiming to optimize the transesterification process critical for converting waste oils and fats into biodiesel. Kumar et al. used optimization of process parameters to increase transesterification efficiency from 74 to 94 % [192]. Genetic engineering of microorganisms, such as bacteria and yeast, was another avenue investigated to improve lipid production for biodiesel. The concept of integrated biorefineries gained traction, aiming to maximize resource utilization from various waste streams. Additionally, advancements in waste-to-energy platforms were explored, encompassing biodiesel, biogas, and bioelectricity production. Researchers worked on process optimization and scalability, addressing economic viability.

8.2. Agricultural waste

Producing biodiesel from agricultural waste faces several challenges. Firstly, agricultural residues' inconsistent availability and quality pose logistical and operational hurdles, demanding sophisticated collection and preprocessing systems. The competition for these residues with other agricultural applications, such as animal feed or soil enhancement, further complicates the reliable sourcing of feedstock. Technological complexities arise in developing efficient processes that can handle the diverse compositions of agricultural waste while maintaining cost-effectiveness. Economic viability is a key concern, encompassing the costs associated with collection, preprocessing, and conversion, which must be competitive with conventional diesel production [193]. Additionally, navigating environmental considerations, such as land use and water consumption, is crucial for ensuring the overall sustainability of biodiesel from agricultural waste [52]. Policy and regulatory support are vital for fostering a conducive environment, and without it, the full potential of this renewable energy source may remain untapped [176]. In recent years, the biodiesel industry has witnessed promising advancements, especially in the realm of biodiesel production from industrial waste. Researchers are diligently exploring innovative approaches to expand the range of industrial waste utilized as feedstocks, aiming to enhance both efficiency and sustainability. One notable area of progress lies in the development of catalytic processes, where scientists are investigating novel catalysts and reaction conditions to optimize the transesterification process, a key step in biodiesel production [194]. Additionally, there is a growing interest in microbial biodiesel production, leveraging microorganisms like algae and bacteria to offer a potentially more resource-efficient and environmentally friendly alternative. However, process optimization remains a challenge, with ongoing research aimed at refining reaction kinetics, separation techniques, and the overall efficiency of the production chain.

A significant improvement has been made in how to prepare materials for making biodiesel. Novel and optimized techniques, like hydrothermal and enzymatic processes, are being developed to make the useful parts of agricultural waste more accessible [195]. This helps to get more and improved biodiesel. Maneeintr et al. employed a combination of hydrothermal and enzymatic treatments on pineapple waste, resulting in a notable 29.3 % increase in glucose yield and an impressive 226.7 % boost in fructose yield [196]. The catalysts used in making biodiesel have also gotten better. Scientists are working on improving the catalysts and how they work in the chemical process that makes biodiesel. The spinel-structured catalyst of urea, MgO/ $MgAl_2$-O_4, attained 95 % conversion, and the activity was observed to have been retained after six reaction cycles [197]. Ni-doped ZnO nanocomposite yielded 92.5 % biodiesel [198]. Mn-doped ZnO nanocatalyst accomplished 97 % biodiesel from mahua oil [199]. The goal is to minimize both energy consumption and the overall costs. There is also growing interest in using tiny living things, like bacteria and yeast, to directly turn agricultural waste into biodiesel [129]. This could simplify the production process and minimize the steps needed.

8.3. Industrial waste

While holding significant promise for sustainable energy solutions, biodiesel production from industrial waste confronts several challenges that must be effectively addressed for widespread acceptance. A primary hurdle lies in the variability of industrial waste feedstocks, necessitating solutions to manage their diverse compositions consistently. Contaminants and impurities present in industrial waste require meticulous removal during pre-processing to ensure the quality of the final biodiesel. The intricate technological processes involved, such as feedstock pretreatment and transesterification, pose scalability and cost-effectiveness challenges, particularly for smaller production facilities. The economic feasibility of biodiesel production from industrial waste is contingent on achieving competitiveness with traditional fuels, considering costs associated with feedstock collection, processing, and conversion. Glycerol, a byproduct of biodiesel production, poses management challenges, necessitating economically viable utilization or efficient disposal methods. Additionally, the energy intensity of biodiesel production demands a careful balance to ensure a net positive contribution to reducing greenhouse gas emissions. Engine compatibility issues, especially with older engines, and challenges related to cold weather performance require attention to ensure seamless integration into existing transportation infrastructure [200]. Regulatory frameworks significantly impact the growth of the biodiesel market, necessitating clear and supportive regulations. Furthermore, considerations regarding land use and competition with food crops need careful management to ensure environmental sustainability and ethical production practices. Overcoming these challenges needs ongoing research, technological innovation, and collaborative efforts across sectors to unlock the full potential of biodiesel production from industrial waste.

Ultrasonic-assisted transesterification is used as it is considered to be the least energy-intensive method for converting industrial waste to biofuel [201]. Improved methods to recycle waste oils from industrial waste have seen advancements to improve quality by improving oxidation stability, pour point, etc [202]. Process intensification technologies using microreactors, membrane reactors, microwave, reactive distillation, and centrifugal contractors are deployed to overcome issues of low yield purity [27,203].

8.4. Waste cooking oil

The synthesis of biodiesel from waste cooking oil, fish oil, and bones poses some difficulties because of their diverse compositions, necessitating complex processing methods and stringent purification to guarantee fuel of superior quality. Efficient procurement and separation of these waste products create logistical challenges, and pollutants increase the financial and technological barriers. The acquisition of Waste Cooking Oil (WCO) supply poses important obstacles for the biofuel industry in China, leading to inadequate ecological and economic consequences. Low-quality properties are usually present in Waste Cooking Oil (WCO), widely used in the biodiesel industry. The resulting environmental effects are worsened by this quality issue, which also increases the pretreatment phase complexity [204].

The synthesis of biodiesel from waste cooking oil has been significantly advanced in recent years, emphasizing improved conversion procedures, cutting-edge technology, and a greater industry commitment to sustainability. The focus has been on improving the quantity and quality of biodiesel by refining the process of turning used cooking oil into biodiesel. Ultrasound-aided techniques are being used to optimize the process [205]. When ultrasonic irradiation passes from a solvent solution, it generates expanding and compressing areas, resulting in bubbles. These bubbles then break down into highly energetic tiny environments with extreme pressures and temperatures approaching 5000 K, and kilobar ranges on nano time frames, leading to more rapid reaction [206]. The use of novel catalysts like walnut shells and artificial intelligence techniques are being used to achieve cost-effectiveness [207]. The use of nanoparticles like zinc oxide for better performance and emissions of biodiesel [208]. Moreover**,** novel blends like toluene biodiesel blends are used to get better performance [139].

8.5. Waste animal fats

The varied chemical properties of waste fats from animals present a problem in the manufacturing of biodiesel, requiring strong purifying procedures to satisfy strict fuel requirements. The logistics involve securing and overseeing an uninterrupted supply of such fats on a large scale, reconciling the necessity for refinement to produce high-quality fuel.

The recent advancements in the production of biodiesel derived from waste animal fats have showcased progress across various fronts in the industry. The primary focus has been refining conversion processes to efficiently convert waste animal fats into biodiesel, aiming to enhance production yield and product quality. The production of biodiesel from animal fats using non-catalytic supercritical methods [209]. The research trends involve new catalysts from cost-effective sources like cow horns and shells [210]. Other research highlights the use of solid carbon catalysts made of sulfonated cellulose to accelerate the microwave-induced conversion of oleic acid into methyl oleate or biodiesel. Because of the remarkable reusability of the catalyst, ease of manufacture, and effectiveness in performance, the research emphasizes its potential to support the manufacturing of sustainable biodiesel [211,212].

8.6. Algae

Scalability issues with growth techniques affect the capacity of algae-based biodiesel to fulfill significant fuel requirements. Another challenge is the harvesting of algae. The energy and labor-intensive manual dewatering process drives the search for efficient harvesting techniques for microalgae. Bioflocculation requires assessing growth kinetics, contaminating hazards, and optimal doses. To overcome economic hurdles, separate ponds for flocculating algae cultivation are needed. Despite conventional and low-cost harvesting techniques, efficient algal cell isolation remains a challenge [213]. Commercial viability is impacted by energy-intensive extraction and conversion operations and technical challenges in improving algal growing conditions. The difficulties in determining if massive amounts of algae-derived biodiesel are commercially feasible are made more difficult due to high initial costs for cutting-edge technologies.

The developments in the realm of algae-based biodiesel production represent noteworthy strides across various aspects of the industry. The primary focus has centered on refining cultivation and extraction methodologies to optimize both the quantity and quality of biodiesel obtained from algae. Innovations in cultivation methods, including advancements in controlled environments and novel harvesting techniques, have resulted in heightened efficiency and productivity levels. A recent study investigates the use of food waste hydrolysis products and temperature manipulation to enhance biomass and lipid yields in modified Phaeodactylum tricornutum, potentially increasing biofuel production cost-effectively [214]. Microalgae's ability to produce bioenergy and their combination for wastewater treatment offer benefits for the environment and economy [215].

9. Environmental impact

The ever-growing energy demand and the damage that the consumption of fossil fuels causes to the environment are the driving forces behind the search for more sustainable sources of energy [216]. Because biodiesel has the potential to mitigate the environmental consequences associated with traditional fossil fuels, there has been much interest in exploring it as an alternative fuel source. Biodiesel is marketed as an eco-friendly and renewable alternative with the potential to reduce emissions of hazardous pollutants such as particulate matter and greenhouse gases that degrade air quality [217,218]. This seeks to give an in-depth overview of biodiesel's environmental effects, highlighting its potential benefits and ecological issues in the context of sustainable energy. Various biodiesel resources contribute variably to the field of eco-friendly energy solutions, displaying varying environmental implications and aligning uniquely with the goals of sustainable development (SDGs), as shown in Fig. 13. Biodiesel can significantly reduce CO_2 emissions compared to petroleum diesel. This is because the carbon dioxide released during combustion is offset by the CO_2 absorbed by the plants during their growth phase, making it a carbon–neutral cycle to some extent [219].

Utilizing waste oils, especially waste cooking oil and fish oil-based biodiesel, helps achieve SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action) by reducing reliance on renewable energy sources. This creative use is an excellent illustration of SDG 9 (Industry, Innovation, and Infrastructure), which places a strong emphasis on the development of environmentally friendly technology and efficient use of resources. On the other hand, extreme caution concerning the environment is necessary when producing biodiesel from bones to minimize any possible negative effects on the ecosystems of land as well as water. This is in line with SDGs 14 (Life under Water) and 15 (Life on Land), which highlight the need to give careful consideration to ecological diversity and conservation of habitat in the processes used to produce biodiesel. Regardless of its potential for economic benefit, waste animal fat-derived biodiesel requires strict environmental oversight to meet SDG 8 (Decent Work and Economic Growth) without affecting social fairness

Table 5
The viability and economic feasibility of biodiesel-producing waste sources.

Waste sources	Viability			Economic feasibility		
	Availability	Processing	Yield	Cost	Market	Challenges
Waste cooking oil	Extensively available as a byproduct of the food industry and households.	Requires pretreatment to remove impurities and free fatty acids before transesterification	Generally high, depending on the quality of the collected oil.	Low raw material cost since it's a waste product. Collection and pretreatment costs are relatively low.	Established market with existing infrastructure for collection and processing.	Variability in quality and potential contamination can increase processing costs.
Animal Fats	Byproduct of the meat processing industry; significant quantities are available.	Requires pretreatment to remove solid residues and reduce free fatty acids.	Moderate to high, dependent on the type of animal fat.	Low raw material cost as it is a waste product, but collection and rendering can be costly.	The existing market for tallow and lard; biodiesel from animal fats is used in blends.	High free fatty acid content can complicate the transesterification process and increase costs.
Algae	Cultivated specifically for biodiesel production, with high growth rates.	Requires cultivation, harvesting, drying, and lipid extraction; energy intensive.	Potentially very high lipid content, leading to high biodiesel yields.	High initial investment and operational costs for cultivation and processing.	Emerging market; research and development are ongoing to improve cost efficiency.	High capital and operational expenses, technology development needed to reduce costs.
Organic Residues	Includes agricultural residues (e.g., straw, husks), food waste, and other organic waste.	Requires collection, pretreatment, and sometimes fermentation to produce lipids.	Variable, dependent on the type of residue and processing efficiency.	Low raw material cost: however, collection and pretreatment can be labor-intensive and costly.	Potentially large market; waste management policies can support biodiesel production.	Variability in feedstock composition and availability can impact consistency and cost of production.

or food supply chains.

Concurrently, within biodiesel resources, biodiesel produced from algae shows promise and is good for the environment. The effectiveness of microalgae as a feasible alternative for biofuel production has been highlighted by recent studies because of its affordable cultivation, quick growth, and capacity to adapt to harsh conditions. Furthermore, many microalgae species are photosynthetic, meaning they can absorb carbon dioxide (CO_2) using solar radiation. This shows great potential for microalgae as a sustainable bioenergy source [216]. The overall effects of incorporating algae farming into wastewater treatment systems significantly reduced their negative effects on the environment [220]. Using CO_2 to propel growth has no environmental effect and complies with SDG 9 (Industry, Innovation, and Infrastructure) as it uses cutting-edge energy production techniques without overusing freshwater resources or land for agriculture. By offering flexible sources of energy, this biodiesel variety helps achieve SDG 11 (Sustainable Cities and Communities) by lowering dependency on fossil fuels, especially in urban areas. Moreover, SDG 17 (Partnerships for the Goals) highlights the importance of collaboration endeavors, and algae-based biodiesel promotes multidisciplinary cooperation to create sustainable energy technology. Its prudent use of non-agricultural land and limited freshwater resources aligns with the overall goal of the United Nations' Sustainable Development Agenda.

The production of biodiesel from waste sources is governed by regulatory frameworks and standards aimed at ensuring environmental sustainability and product quality. These regulations typically include guidelines for feedstock sourcing, production processes, emissions control, and waste management. Standards such as ASTM D6751 and EN 14214 specify the requirements for biodiesel quality, covering parameters like purity, viscosity, and sulfur content to ensure compatibility with existing diesel engines and minimal environmental impact. To promote biodiesel production from waste sources globally, harmonized policies are crucial. These policies should establish unified standards for biodiesel quality, ensuring consistency and compatibility across regions. Sustainability criteria must be implemented to safeguard against environmental degradation and social impacts, akin to the EU's Renewable Energy Directive. Coordinated financial incentives like tax credits and subsidies are needed to encourage investment. International collaboration in research and development is essential to advance biodiesel technologies. Harmonized infrastructure policies can optimize waste collection and processing. When considering the full lifecycle from production to combustion, biodiesel generally results in lower greenhouse gas (GHG) emissions. Studies have shown that biodiesel can reduce lifecycle GHG emissions by up to 80 % compared to conventional diesel [221]. Large-scale biodiesel production from waste sources can potentially reduce food security concerns over biodiesel production. This is especially relevant when food crops like soybeans or corn are used as feedstocks. The expansion of biodiesel feedstock plantations, particularly palm oil in tropical regions, can lead to deforestation, loss of biodiversity, and significant carbon emissions from the destruction of carbon-rich ecosystems. That is why this article focuses on biodiesel production from waste sources in order to maintain balance in the ecosystem. Public awareness campaigns should promote waste-to-energy solutions. Streamlined regulatory frameworks will reduce bureaucratic obstacles, facilitating biodiesel production approvals. Facilitating international trade and removing trade barriers will foster market development. Standardized environmental impact assessments are necessary to ensure adherence to global standards. Finally, integrating biodiesel policies across sectors such as agriculture and energy will support sustainable development goals.

10. Economic feasibility & viability

Biodiesel production from waste sources is a promising approach to sustainable fuel. Each source presents unique pros and cons concerning viability and economic feasibility. Table 5 represents the matrix between the biodiesel-producing waste sources dependent on their viability and economic feasibility. Waste Cooking Oil (WCO) and Animal Fats are currently the most economically feasible options due to their low cost and established collection and processing infrastructure. In 2022, the global supply of waste cooking oil (WCO) was approximately 3.7 billion gallons [222]. The pretreatment is required to remove impurities like free fatty acid before transesterification [223]. The yield rate of biodiesel production from WCO varies depending on the catalyst and process used. When using calcium oxide as a catalyst derived from chicken eggshells, a biodiesel yield of up to 100 % can be achieved in a reaction time of 2 h [224]. The catalyst MgO-SnO_2 provides a biodiesel yield of 88 % under optimized conditions of 2 wt% nano-catalyst loading, a methanol-to-oil molar ratio of 18:1, 2 h reaction time, and a reaction temperature of 60 °C [225]. Waste cooking oil is significantly cheaper than virgin oils. For instance, the cost of WCO can be around $0.30–$0.50 per liter with profit margins of 10 to 20 %, whereas virgin vegetable oils can cost between $0.80–$1.00 per liter [226,227]. In 2023, the global market for animal fat reached approximately 28.64 million metric tons (MMT) and is projected to grow to about 33.61 MMT by 2032, reflecting a compound annual growth rate (CAGR) of 2.70 % [228,229]. A study on biodiesel production from waste chicken fat reported a maximum yield of 90.2 % biodiesel using a 2 % catalyst weight and a 2-hour reaction time [230]. Another research indicated that the overall biodiesel yield from various animal fats, including tallow and lard, typically ranges between 85 to 90 % [231]. The economic feasibility of utilizing waste animal fat can vary based on several factors, including processing costs, market demand, and regulatory considerations. Algae present high potential but require technological advancements and cost reductions to become economically viable. Algae biomass production globally is estimated to be around 10,000 to 20,000 tons per year, primarily for biofuels and other applications. Most algae systems today can generate from 2500 gallons up to 5000 gallons of oil per acre annually using 30 % oil content [232]. The production costs of algae-based biofuels have been higher than traditional fossil fuels. However, the advances in algae strain selection, cultivation techniques (open ponds vs. closed photobioreactors), harvesting methods (centrifugation, filtration, etc.), and extraction technologies (solvent extraction, supercritical fluid extraction) have aimed to reduce production costs and increase efficiency. Organic Residues offer significant potential, particularly in regions with robust waste management systems, but economic feasibility depends on the efficiency of collection and processing methods. However, promoting policies supporting waste-to-biodiesel initiatives, investing in research and development to improve processing technologies, and creating incentives for waste collection and biodiesel production can enhance these sources' viability and economic feasibility.

11. Swot analysis

A SWOT analysis is a strategic planning tool that provides a comprehensive framework for evaluating the internal strengths and weaknesses along with external opportunities and threats facing an organization, project, or individual. This methodical examination enables a holistic understanding of the current state and potential future scenarios, allowing for informed decision-making and effective strategic planning. By identifying and assessing these key factors, organizations can capitalize on their strengths, address their weaknesses, leverage opportunities, and mitigate threats, thereby enhancing their overall performance and competitiveness in a dynamic and ever-changing environment.

The exploitation of agricultural waste for biofuel production embodies formidable advantages by capitalizing on abundant and diverse sources of organic materials, such as crop residues and biomass. This renewable feedstock is a dependable resource for biofuel production, thereby diminishing dependence on fossil fuels. The environmental merits are pronounced, as the conversion of agricultural waste into biofuels offers a sustainable alternative, mitigating greenhouse gas emissions and fostering a more environmentally conscious energy paradigm. Furthermore, the cyclical nature of agricultural waste generation ensures a steady supply, augmenting the reliability of biofuel production. Nevertheless, operational challenges arise from logistical complexities and the imperative for efficient collection and processing systems. The variability in waste composition and seasonal availability also poses hurdles in attaining uniform biofuel production standards. The opportunities emerge with advancements in biofuel technology, providing avenues to bolster production efficiency and elevate the overall quality of biofuels derived from agricultural waste. Collaborative endeavors with research institutions and technology providers can drive innovation, paving the way for more sustainable and cost-effective biofuel solutions. Governmental support through incentives and policies favoring biofuel production from agricultural waste further propels the sector, aligning with the global impetus towards renewable energy sources. Despite these opportunities, economic constraints for farmers may pose a threat, as the additional costs associated with implementing advanced biofuel production methods could be challenging, particularly for small-scale agricultural operations. Competitive threats also emanate from alternative biofuel sources and the evolving landscape of renewable energy options, influencing the market penetration of biofuels derived from agricultural waste. Public perceptions regarding the ethical use of agricultural resources for fuel may play a pivotal role in market acceptance, thereby shaping the growth trajectory of biofuels derived from agricultural waste.

The utilization of municipal waste for biofuels introduces compelling strengths, tapping into the consistent and abundant sources of waste generated in urban areas. Municipal waste, comprising diverse materials such as organic waste, serves as a valuable feedstock for biofuel production, offering a sustainable solution to address both waste management challenges and energy needs. The environmental strengths are notable, with the conversion of municipal waste into biofuels contributing to reduced landfill usage, minimized pollution, and a decreased reliance on traditional fossil fuels. Moreover, the continuous generation of municipal waste ensures a reliable and ongoing supply for biofuel production, enhancing the sector's viability. However, operational weaknesses arise from the heterogeneous nature of municipal waste, requiring efficient sorting and processing technologies to achieve uniform biofuel output. Regulatory complexities and compliance issues related to waste disposal standards and environmental regulations add additional challenges, necessitating adherence to stringent guidelines. The opportunities emerge with advancements in biofuel technology, offering potential pathways to enhance the efficiency of municipal waste-derived biofuels. Collaborations with local municipalities, technology providers, and waste management companies can drive innovation, leading to more effective waste-to-energy conversion methods. Governmental support through policies, incentives, and subsidies favoring biofuel production from municipal waste further propels the sector, aligning with the increasing emphasis on sustainable energy solutions. Despite these opportunities, economic constraints for municipalities may pose a threat, as implementing advanced biofuel production methods could incur additional costs. Competitive challenges come from alternative biofuel sources and the evolving landscape of renewable energy options, impacting the market penetration of biofuels derived from municipal waste. Public perceptions regarding the environmental impact and ethical considerations of utilizing urban waste for fuel may influence market acceptance, shaping the growth trajectory of biofuels from municipal waste.

The utilization of industrial waste for biofuels embodies robust advantages, leveraging the substantial and consistent sources of waste generated by industrial processes. Encompassing a variety of materials, such as manufacturing residues and by-products, industrial waste stands as a reliable feedstock for biofuel production, providing an eco-friendly alternative to traditional fossil fuels. These strengths are further underscored by the potential to alleviate waste disposal challenges and

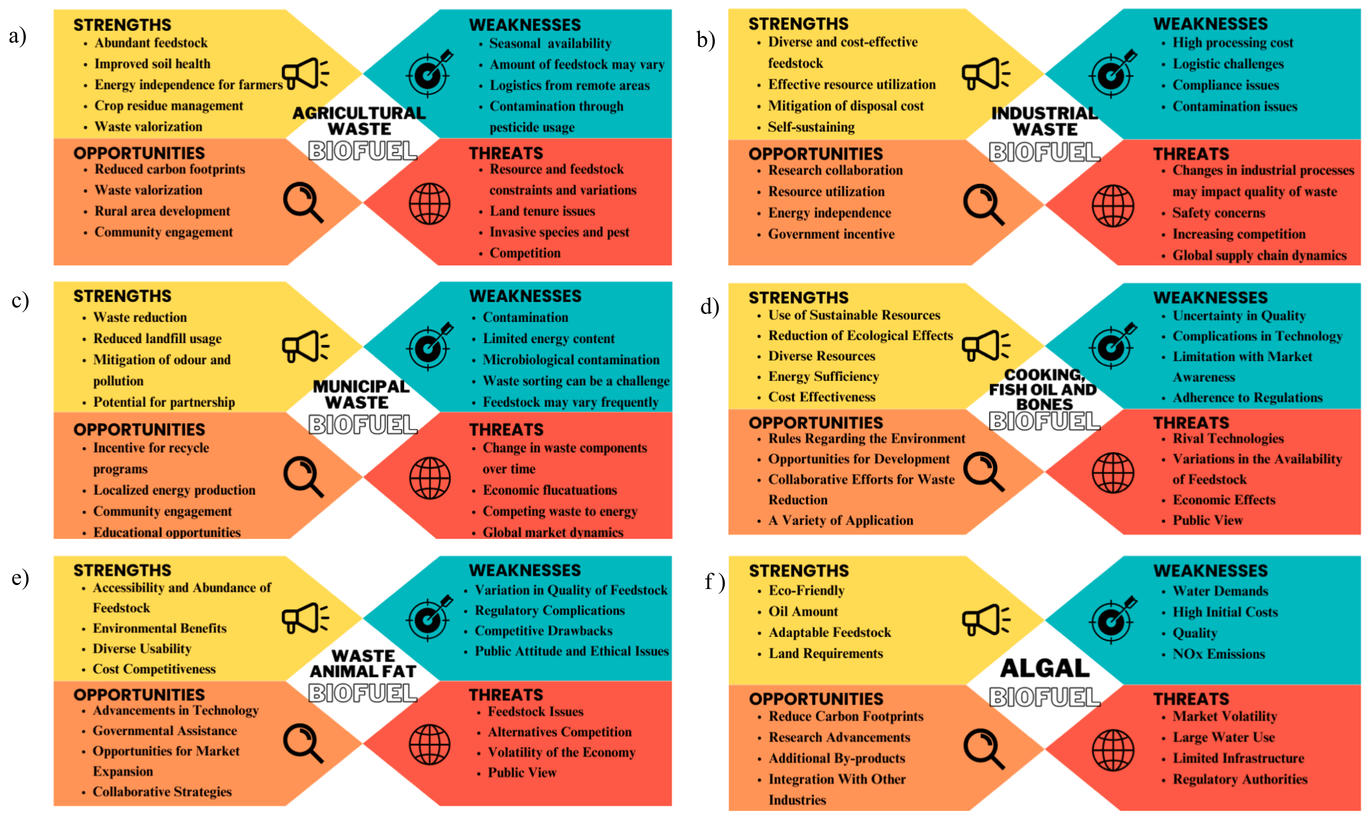

Fig. 14. SWOT Analysis of biodiesel from a) agricultural wastes, b) industrial wastes, c) municipal wastes, d) cooking, fish oil and bones, e) waste animal fats, f) Algae.

reduce dependence on finite resources. However, operational challenges arise from the diverse and complex nature of industrial waste, necessitating advanced technologies for efficient processing and conversion into biofuels. Addressing the variability in waste composition and ensuring the scalability of production processes pose challenges to achieving standardized biofuel output. The opportunities materialize with advancements in biofuel technology, offering avenues to enhance the efficiency of biofuels derived from industrial waste. Collaborative efforts involving industries, research institutions, and technology providers can drive innovation, resulting in more sustainable and cost-effective biofuel solutions. Governmental support through incentives and policies favoring biofuel production from industrial waste further propels the sector, aligning with the global push for renewable energy sources. Despite these opportunities, economic constraints for industries may pose a threat, as the additional costs associated with implementing advanced biofuel production methods could be challenging. Competitive threats also arise from alternative biofuel sources and the evolving landscape of renewable energy options, impacting the market penetration of biofuels derived from industrial waste. Public perceptions regarding the environmental impact and ethical considerations of utilizing industrial waste for fuel may influence market acceptance, thereby shaping the growth trajectory of biofuels from industrial waste.

According to Fig. 14, utilizing waste cooking oil, fish oil, and bones for biodiesel production presents several strengths, including promoting sustainability by reducing the need for new resources, lessening adverse ecological effects through recycling, and providing a diverse array of resources. However, weaknesses arise from uncertainties in biodiesel quality due to varying feedstock, the need for complex and costly conversion processes, market resistance stemming from unfavorable consumer attitudes, and challenges in complying with waste management and biodiesel production regulations. Opportunities lie in support of environmental regulations favoring sustainable fuels, potential innovations through collaborations for waste reduction and optimized usage, research prospects for process enhancement, and exploring wider applications beyond transportation fuel. Conversely, threats stem from competitive technologies in alternative energy, fluctuations in waste feedstock availability impacting reliability, economic fluctuations affecting profitability, and negative public perceptions hindering market acceptance and expansion of biodiesel from waste resources. Strategic planning and technological advancements can capitalize on these strengths and opportunities while addressing weaknesses and threats to further develop and establish the market presence of biodiesel from waste sources. The SWOT analysis of waste animal fat-based biodiesel unveils several critical aspects that shape its position within the renewable energy sector. Strengths lie in the accessibility and abundance of feedstock. Waste animal fat, sourced from various industries, including slaughterhouses and food processing units, is a consistent and ample resource for biodiesel production. Moreover, the environmental benefits offered by this biodiesel variant are substantial, significantly reducing greenhouse gas emissions and contributing to a more sustainable energy landscape. Its diverse usability across existing diesel engine infrastructure further strengthens its appeal, showcasing adaptability and compatibility. Additionally, the prospects of cost competitiveness, driven by technological advancements and the availability of raw materials, signify a potential edge in the market. However, the analysis also highlights several weaknesses. The variation in the quality of feedstock poses a significant challenge, affecting the uniformity and standardization of biodiesel output. Regulatory complications surrounding waste management, animal by-products, and biodiesel production processes add complexity and compliance issues. Moreover, competitive drawbacks emerge due to preferences for other biodiesel sources and concerns related to public attitudes and ethical considerations regarding using animal-derived resources for fuel. Nevertheless, various opportunities present themselves. Advancements in technology offer a pathway to enhance production efficiency and elevate quality standards. Governmental assistance through supportive policies, incentives, or

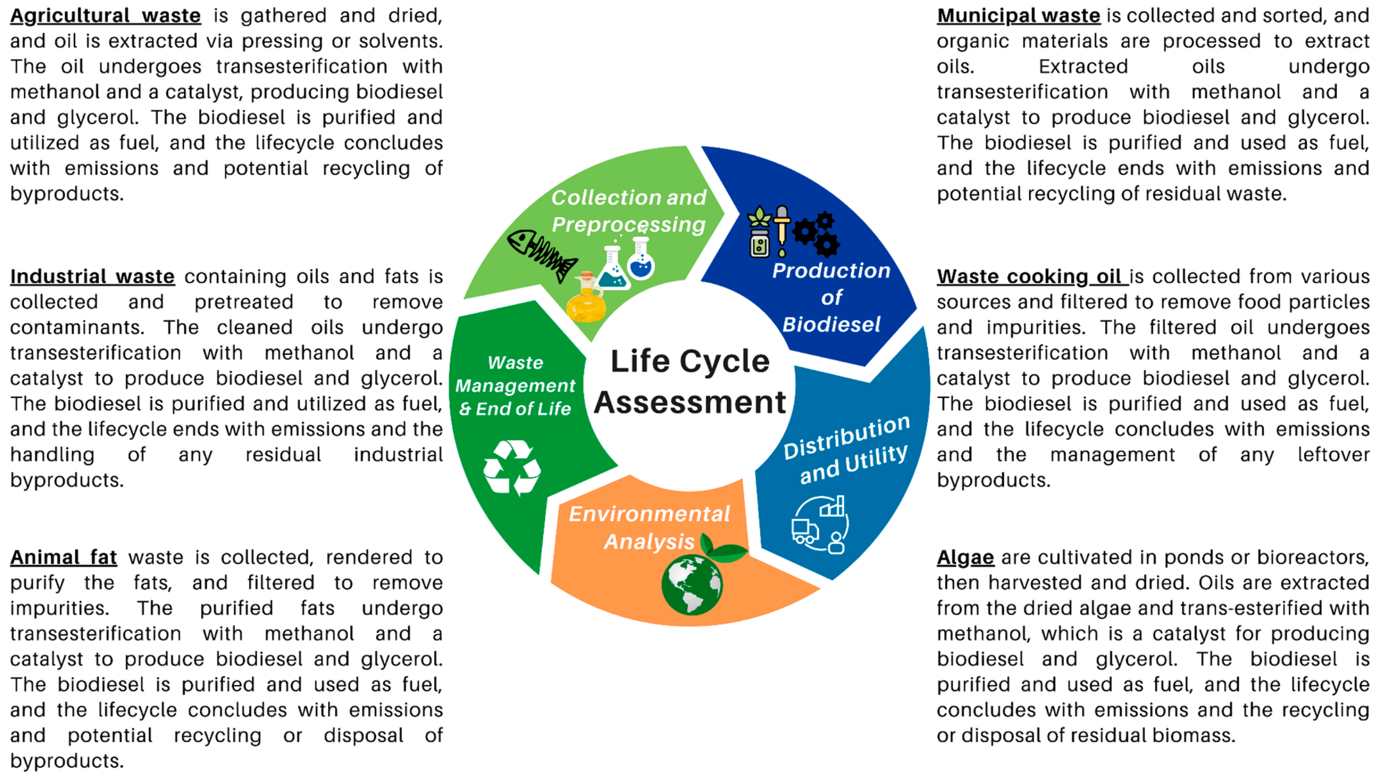

Fig. 15. Life cycle assessment of biodiesel derived from a) agricultural wastes, b) industrial wastes, c) municipal wastes, d) waste cooking, fish oil and bones, e) waste animal fats, and f) Algae.

subsidies could significantly bolster market prospects. Opportunities for market expansion abound as awareness grows around sustainable energy sources, fostering a conducive environment for biodiesel uptake. Collaborative strategies with industries generating waste animal fat can ensure a consistent and reliable supply chain for feedstock, providing a strategic advantage. The issues related to feedstock availability and stability pose a risk to production consistency, potentially disrupting operations. Intense competition from alternative biodiesel sources and emerging renewable energy options could hinder market penetration. Economic volatility, characterized by fluctuating oil prices or alterations in governmental policies, presents a risk to the cost-effectiveness of waste animal fat-based biodiesel. Additionally, public perceptions regarding using animal-derived resources for fuel might significantly influence market acceptance and growth trajectories.

Algae-based biodiesel presents a compelling alternative to conventional fossil fuels, characterized by several notable strengths. Its eco-friendly nature aligns with sustainable energy goals, offering a renewable source significantly reducing greenhouse gas emissions. Algae's high oil content stands as a promising advantage for biodiesel production, coupled with its adaptability to diverse environments and minimal land requirements, mitigating concerns about competition with food crops. However, this burgeoning industry faces significant challenges. High water demands for algae cultivation, particularly in water-stressed regions, pose limitations. Furthermore, the initial capital investment required for setup and infrastructure development remains a substantial hurdle. Quality consistency and the potential for NOx emissions during biodiesel production from certain algae strains are additional weaknesses that demand technological refinement and standardization attention. Amid these challenges, opportunities abound for algae-based biodiesel. The capacity to substantially reduce carbon footprints aligns with global climate objectives. Continuous research endeavors hold promise for technological advancements, optimizing cultivation techniques, and refining biodiesel production processes. Moreover, the generation of valuable by-products, such as animal feed or pharmaceuticals, from algae cultivation presents an avenue for economic diversification. Collaborative integration with industries like wastewater treatment or agriculture is a strategic opportunity to foster mutually beneficial partnerships and leverage shared resources. However, market volatility and fluctuations in oil prices present inherent threats to the competitiveness and wider adoption of algae-based biodiesel. Additionally, concerns regarding water scarcity, inadequate infrastructure, and evolving regulatory landscapes pose significant challenges to its commercial scalability and wider implementation.

12. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) provides a comprehensive evaluation of the environmental impacts associated with a product, process, or activity throughout its entire life cycle. The LCA is a methodological and science-based approach that considers all stages of a product's life, from raw material extraction to production, use, and disposal. The LCA of various biodiesel feedstocks, including agricultural waste, industrial waste, municipal waste, waste cooking oil, fish oil, waste bones, waste animal fat, and algae, involves a comprehensive evaluation of their environmental impact and sustainability across distinct life cycle stages. The evaluation begins with the collection phase, followed by pre-processing steps to optimize raw materials for biodiesel production. The production phase involves triglyceride extraction through processes like transesterification, with a focus on energy, water, and chemical usage. Transportation and combustion stages are analyzed for emissions, including pollutants such as COx, SOx, NOx, and HC particulates. The comprehensive LCA incorporates a systematic methodology for analyzing emissions during transportation and combustion stages, ensuring a meticulous evaluation of environmental implications. Fig. 15 highlights the importance of responsible resource utilization and waste management, contributing significantly to a more sustainable future across the complete life cycle of biodiesel production. Additionally, the distribution and utility phase assesses environmental implications during biodiesel transport and utilization, considering factors like greenhouse gas production, air contaminants, and potential health risks. The LCA also addresses waste management plans, emphasizing responsible resource utilization and waste management for sustainability. The systematic methodology underscores the importance of minimizing environmental impact and waste throughout the life cycle of biodiesel, as explained in Fig. 15.

The analysis extends to specific feedstocks such as industrial waste, municipal waste, and waste animal fat, detailing their unique preprocessing and production processes. The LCA methodology aims to identify the most environmentally friendly feedstock for biodiesel production and provides strategic guidelines for maximizing productivity while minimizing environmental impact. In the case of algae-based biodiesel, the LCA involves a multifaceted approach, considering cultivation, harvesting, oil extraction, conversion, distribution, and combustion phases. Environmental facets under scrutiny include greenhouse gas emissions, energy efficiency ratios, resource depletion, ecotoxicity, and land requirements. The LCA serves as a tool for pinpointing areas with pronounced environmental impacts and guiding strategies to mitigate these effects, acknowledging the influence of contextual factors on assessment outcomes.

13. Future prospects

Biodiesel production from municipal waste is poised for significant advancements driven by technology and sustainability goals. Efforts in research and development aim to optimize efficiency and yield through improved feedstock utilization, catalyst development, and process optimization. Integration of advanced technologies such as artificial intelligence and automation promises further refinement, enhancing the economic viability and environmental friendliness of municipal waste biodiesel. Supportive policies and increasing consumer awareness are expected to accelerate adoption, positioning municipal waste biodiesel as a pivotal player in sustainable energy transitions. The future prospects of biodiesel produced from municipal waste are highly promising, driven by ongoing advancements in technology and an increasing focus on sustainable energy solutions. Continued research and development are likely to enhance the efficiency and yield of biodiesel production from municipal waste, with innovations in feedstock utilization, catalyst development, and process optimization [233]. The integration of advanced technologies, such as artificial intelligence and automation, could further elevate the monitoring and control of production processes. The exploration of advanced feedstock options, including diverse waste streams and bio waste and proficient enzymes [234] may broaden the materials suitable for biodiesel production, ensuring a more versatile and adaptable approach. The circular economy principles underpinning municipal waste biodiesel align with a holistic waste-to-energy perspective, contributing to comprehensive resource management. For example, the Pilgrimage in Makkah during animal slaughter each year produces 13 % fat content from municipal waste with a potential of 6.4 thousand tons of biodiesel production in a year [235].

The prospects of biodiesel produced from agricultural waste are shaped by a range of promising trends, reflecting a global shift towards sustainable and renewable energy solutions. One key avenue of development involves the diversification of agricultural feedstocks. Ongoing research seeks to expand the range of agricultural residues and waste streams used for biodiesel production, optimizing resource utilization and bolstering the sustainability of the process. Furthermore, new untapped agricultural wastes can be tested that burn efficiently in diesel engines. Kandaswamy et al. [236] recently tested cashew nut shell oil as a likely feedstock for biodiesel production. The future of biodiesel from agricultural waste hinges on diversifying feedstocks and advancing conversion technologies. Ongoing research explores novel agricultural residues and waste streams for biodiesel production alongside innovations in catalytic and microbial processes. Genetic engineering efforts seek to enhance feedstock plants for better suitability in biodiesel production, guided by circular economy principles that align with global sustainability objectives. Advanced conversion technologies constitute another focal point for the future. Innovations in catalytic processes, enzymatic methods, and other conversion technologies aim to boost the efficiency of biodiesel production. These advancements are crucial for making biodiesel more cost-effective and environmentally friendly, aligning with the overarching goals of sustainable energy solutions. Mahmud et al. [237] proposed the potential to extract 44.4 million metric tons of bioethanol annually from agricultural residues.

The prospects of biodiesel derived from industrial waste are exceptionally promising, underpinned by several key trends that signal a transformative trajectory for this sustainable energy source. As global attention intensifies on environmental sustainability, biodiesel from industrial waste stands out as a pivotal player in the quest to reduce carbon emissions and mitigate ecological impact [51]. Biodiesel derived from industrial waste holds the potential to mitigate carbon emissions and environmental impact. Technological advancements in catalysts and waste utilization techniques aim to boost efficiency and cost-effectiveness, with diversification of feedstocks and supportive governmental policies expected to drive widespread adoption. Emerging research focuses on converting waste cooking oil, fish oil, and bone lipids into biodiesel, leveraging innovations in chemical processes and catalysts to improve conversion efficiency and advance renewable energy goals. Utilizing waste animal fats for biodiesel production offers a sustainable alternative to fossil fuels, supported by advancements in catalytic processes and conversion technologies. These efforts not only reduce environmental impact but also enhance waste management practices, contributing to a cleaner energy future. The potential of algae-derived biodiesel is bolstered by ongoing research to enhance production efficiency and explore diverse feedstocks, facilitated by collaborations with agriculture and wastewater treatment industries to scale up algae cultivation for biodiesel production and reduce reliance on non-renewable resources.

In short, future advancements and research directions to enhance the effectiveness, sustainability, and scalability of biodiesel production from waste sources span critical domains. Innovations in feedstock utilization, including supercritical fluid processing, enzymatic hydrolysis and microbial fermentation, hold promise for converting diverse waste materials into biodiesel precursors more efficiently. Additionally, exploring advanced conversion technologies such as supercritical fluid processing and novel catalysts aims to boost process efficiency while cutting energy demands. Optimizing the production process to improve efficiency and integrating biodiesel production with circular economy principles, such as co-locating facilities with waste treatment plants for biogas utilization and incorporating algae cultivation for biomass, seeks to improve resource effectiveness and sustainability. Furthermore, optimizing energy use through heat integration and process intensification, alongside valorizing biodiesel by-products like glycerol for high-value chemicals, promises enhanced economic viability and environmental benefits. Scaling these technologies from lab to industrial scale, supported by rigorous life cycle assessments and conducive policy frameworks promoting renewable fuels, is pivotal for unlocking biodiesel's full potential from waste sources globally.

14. Conclusions

The biodiesel sources, waste cooking oil, fish oil, bones, waste animal fats, and algae are all thoroughly reviewed for feasibility using performance indicators, combustion behaviors, and emissions levels. Using these sources comes with intrinsic strengths, weaknesses, opportunities, and threats that are found through rigorous SWOT analysis. Current developments in biodiesel production processes are conducted through a lifecycle evaluation as part of our study, with a strong emphasis on innovation for increased sustainability and efficiency, as mentioned below:

- All the biodiesel-producing waste sources are found beneficial in reducing engine exhaust emissions (CO and HC). However, they are responsible for higher NOx and CO_2 emissions due to their higher oxygen content. The biodiesel produced from waste sources like municipal waste and algae produced lower CO_2 emissions.
- All biodiesel-producing waste sources depict significant improvement in engine performance in terms of higher brake power, lower brake-specific fuel consumption and higher brake thermal efficiency.
- The advancements in feedstock utilization, including supercritical fluid processing, enzymatic hydrolysis and microbial fermentation, hold promise for converting diverse waste materials into biodiesel precursors more efficiently. Moreover, advanced conversion technologies such as supercritical fluid processing and novel catalysts aim to boost process efficiency while cutting energy demands.
- Optimizing the production process to improve efficiency and integrating biodiesel production with circular economy principles, such as co-locating facilities with waste treatment plants for biogas utilization and incorporating algae cultivation for biomass, seeks to improve resource effectiveness and sustainability.
- Furthermore, optimizing energy use through heat integration and process intensification, alongside valorizing biodiesel by-products like glycerol for high-value chemicals, promises enhanced economic viability and environmental benefits. Scaling these technologies from lab to industrial scale, supported by rigorous life cycle assessments and conducive policy frameworks promoting renewable fuels, is pivotal for unlocking biodiesel's full potential from waste sources globally.
- Anticipated technological advancements in biodiesel production processes, particularly innovations in catalysts and waste utilization techniques, are poised to play a vital role in significantly enhancing both efficiency and cost-effectiveness, further establishing industrial waste-derived biodiesel as a sustainable and impactful energy solution.
- WCO and Animal Fats are currently the most economically feasible options due to their low cost and established collection and processing infrastructure. The production costs of algae-based biofuels have been higher than traditional fossil fuels. However, the advances in algae strain selection, cultivation techniques (open ponds vs. closed photobioreactors), harvesting methods (centrifugation, filtration, etc.), and extraction technologies (solvent extraction, supercritical fluid extraction) have aimed to reduce production costs and increase efficiency.
- However, promoting policies supporting waste-to-biodiesel initiatives, investing in research and development to improve processing technologies, and creating incentives for waste collection and biodiesel production can enhance these sources' viability and economic feasibility.

CRediT authorship contribution statement

Muhammad Ali Ijaz Malik: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sadaf Zeeshan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Muhammad Khubaib:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Adeel Ikram:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Data curation, Funding acquisition. **Fayaz Hussain:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Hayati Yassin:** Writing – review & editing, Resources, Funding acquisition. **Atika Qazi:** Writing – review & editing, Visualization.

Declaration of competing 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 paper.

Data availability

Data will be made available on request.

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