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Review

Production of Biodiesel from Industrial Sludge: Recent Progress, Challenges, Perspective

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Abstract: This study investigated biodiesel production from industrial sludge, focusing on the feasibility and sustainability of converting waste materials into renewable energy sources. This study combines a comparative analysis of various sludge-based biodiesel production methods, highlighting both their environmental benefits and economic potential. Utilizing physical, chemical, and biological pre-treatments, this study optimizes biodiesel yield while assessing the impact of each method on the overall production efficiency. Key findings revealed that industrial sludge provides a viable feedstock, contributes to waste reduction, and reduces greenhouse gas emissions. The novel contributions of this study include a detailed economic assessment of biodiesel production from sludge and a comprehensive environmental impact evaluation that quantifies the potential sustainability benefits. Limitations related to scale-up processes are identified, and solutions to overcome these issues are discussed to improve industrial feasibility. Furthermore, the integration of sludge-based biodiesel production with other renewable energy systems has been explored as a future avenue to enhance energy efficiency and sustainability. This research contributes to a significant scientific niche by addressing scalability challenges and proposing future perspectives for sustainable biodiesel production from industrial waste.

Keywords: industrial effluents; bio-based product recovery; circular economy; biodiesel production; industrial sludge utilization; sustainable biorefinery

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1. Introduction

1.1. Background on Biodiesel Production

The demand for renewable energy sources has surged in recent years, and biodiesel has emerged as a promising alternative fuel. Biodiesel, derived from organic sources such as algae, vegetable oils, and animal fats, is a sustainable fuel that offers significant environmental benefits. Unlike fossil fuels, biodiesel is biodegradable, nontoxic, and renewable, making it an attractive option for reducing greenhouse gas emissions and mitigating climate change. Its production and use help reduce the dependence on finite petroleum resources, aligning with global efforts to transition to cleaner energy sources and improve energy security [1].

One of the main advantages of biodiesel is its combustion efficiency and reduced environmental impact. Compared to conventional petroleum-based diesel, biodiesel produces lower carbon dioxide emissions (CO_2), sulfur compounds, and particulate matter. This decrease in harmful emissions addresses critical issues such as air pollution and improves public health and environmental quality. Additionally, the versatility of biodiesel allows it to be produced from various feedstocks, including waste oils and fats, agricultural crops, and algae. This adaptability provides a sustainable pathway for waste management and supports the principles of a circular economy by utilizing by-products and waste materials for fuel production [2].

The social and economic implications of biodiesel production are also noteworthy, especially in rural areas, where agricultural by-products can be repurposed. Developing biodiesel facilities can stimulate local economies, create jobs, and increase the demand for agricultural output, adding value to the agricultural sector. Furthermore, biodiesel is compatible with existing diesel engines and infrastructure, making it an accessible and practical solution for reducing fossil fuel consumption and advancing toward a more sustainable energy future [3].

Historically, biodiesel production has primarily relied on vegetable oils and animal fats. Common sources include high-lipid oils such as sunflower, canola, palm, and soybean oils, as well as animal-derived fats, such as beef tallow and chicken fat. These feedstocks played a crucial role in the early development of the biodiesel industry, enabling advancements in research, technology, and commercialization. However, traditional feedstocks face significant challenges, including concerns over the food-versus-fuel debate, land-use changes, and the environmental impact of large-scale agricultural operations [4,5]. It is common to use vegetable oils like sunflower oil, canola oil, palm oil, and soybean oil because they are high in fat and are grown and made in ways that have been shown to work in the past. Animal fats, such as beef tallow and chicken fat, have been extensively used, especially in places where livestock farming is important [6]. These raw materials are important in the early stages and growth of the biodiesel industry. They have enabled research and technological progress, and commercialized biodiesel production. However, traditional raw materials have many problems. Many people are worried about how crops used for food and fuel can compete with each other, how land use can change in ways that are not good, and how large-scale farming affects the environment.

To address these challenges, research has expanded to alternative feedstocks that do not compete with food resources. Non-edible oils such as Jatropha and Camelina oil, waste oils such as used cooking oil, and industrial by-products such as glycerol are increasingly being explored as viable alternatives. These options alleviate the pressure on food supplies and contribute to the sustainability of biodiesel production by promoting the reuse of waste materials. Such innovations underscore the importance of biodiesel in advancing sustainable energy practices, and align with the broader objectives of a circular economy [7,8]. These alternatives not only help ease the stress on food resources, but also encourage the use of waste materials, which further aligns biodiesel production with the ideas of sustainability and the circular economy.

The increasing global demand for renewable and sustainable energy sources has positioned biodiesel production as a vital research and development area. Biodiesel, primarily derived from lipid-rich feedstocks, offers a promising alternative to fossil fuels because of its biodegradability, low toxicity, and ability to significantly reduce greenhouse gas emissions compared to conventional diesel. Industrial sludge, a byproduct of various manufacturing and treatment processes, has recently garnered attention as a viable biodiesel feedstock owing to its lipid content and potential for reducing environmental waste. However, the efficient conversion of industrial sludge into biodiesel requires overcoming several challenges, including the variability in sludge composition, contaminants, and high processing costs.

This study addresses these challenges by exploring innovative approaches to optimize biodiesel production from industrial sludge, focusing on enhancing the process efficiency, yield, and economic feasibility. Key research objectives include evaluating the lipid content and quality of biodiesel derived from sludge, assessing pre-treatment methods to improve conversion rates, and analyzing economic factors to establish a cost-effective production pathway. By investigating these aspects, this study aims to provide valuable insights into the scalability and sustainability of biodiesel production from unconventional feedstocks, such as industrial sludge. The significance of this research lies in its dual environmental and economic benefits; it offers a pathway for repurposing industrial waste while providing a renewable energy source that could reduce reliance on fossil fuels. Additionally, the potential for large-scale sludge-to-biodiesel conversion aligns with circular economy principles, allowing industries to mitigate waste disposal costs and environmental impact. This study ultimately seeks to bridge the existing knowledge gaps in sludge-based biodiesel production, supporting global efforts to transition towards cleaner and more sustainable energy systems.

1.2. Rationale for Using Industrial Sludge

Industrial sludge, which is produced by many industrial processes, presents an unexplored and encouraging opportunity for biodiesel manufacturing. This sludge is produced by many industries such as wastewater treatment plants, pulp and paper mills, food processing facilities, and chemical manufacturing plants. Industrial sludge is a diverse mixture of organic matter, suspended solids, water, and small amounts of unwanted substances. These components are produced in various industrial operations. Worldwide production of industrial sludge is significant and ongoing, offering a conveniently accessible resource. Nevertheless, its composition might vary considerably based on the particular sector, the raw materials utilized, and the treatment techniques employed. In addition to industrial sludge, waste products, including fats, oils, and greases (FOGs), have shown considerable promise as raw materials for biodiesel generation. Typical constituents of industrial sludge consist of FOGs (fats, oils, and greases), lignocellulosic materials (such as wood and plant fibers), organic acids, and inorganic particles [9]. Using industrial waste as a raw material for biodiesel production provides the following advantages in terms of both environment and economy:

- Resource utilization and waste minimization: Utilizing industrial sludge for biodiesel production positively affects waste disposal, helping minimize the environmental consequences of landfilling or incineration. This approach is in line with the principles of circular economy by valuing waste materials and minimizing resource waste [10]. The transformation of waste into valuable resources can improve the efficiency of the industrial processes.
- Carbon footprint reduction: Industrial sludge-derived biodiesel can significantly decrease greenhouse gas emissions compared to fossil diesel. Transforming organic waste into sustainable fuel reduces the overall carbon emissions associated with biodiesel manufacturing, thus aiding worldwide efforts to mitigate climate change [11]. It is important to note this benefit, especially because the government is paying more attention to reducing carbon emissions in many areas.
- Cost savings: Industrial sludge is commonly regarded as a by-product that requires expensive disposal or treatment. The production of biodiesel from inexpensive or free raw materials makes this method more economically viable. Such changes could significantly reduce production costs, making the biofuel industry more competitive [12,13]. Recycling trash into fuel is an excellent way to save money and attract more people to using biodiesel.
- Security and independence in energy: Using sewage from factories as fuel for making biodiesel helps reduce reliance on traditional crops and oils that come from food. This improves energy security by lowering reliance on imported fossil fuels and lowering

the chances of food and fuel production going against each other [14]. Expanding the range of raw materials used in biodiesel production enhances supply chain durability.

Figure 1 illustrates the transition from traditional biofuels to sustainable biofuel generation within a circular economic framework. The figure is divided into the following three main sections, each representing distinct biofuel generation based on its feedstock sources:

- First-generation biofuels: These biofuels are primarily derived from food-based crops such as corn, sugarcane, and vegetable oils. Although these feedstocks were initially advantageous for biofuel production, concerns have arisen regarding their competition with food resources and their potential impact on food security.
- Second-generation biofuels: The next stage involves the use of non-food-based biomass, including lignocellulosic materials, such as wood, crop residues, and other agricultural waste. This shift aimed to reduce reliance on food crops and improve sustainability by utilizing waste products.
- Third-generation biofuels: The latest advancements involve algae and other fast-growing microorganisms that are capable of high lipid production. Biofuels represent a sustainable approach to bioenergy, leveraging renewable resources that require minimal land and water compared to traditional crops.

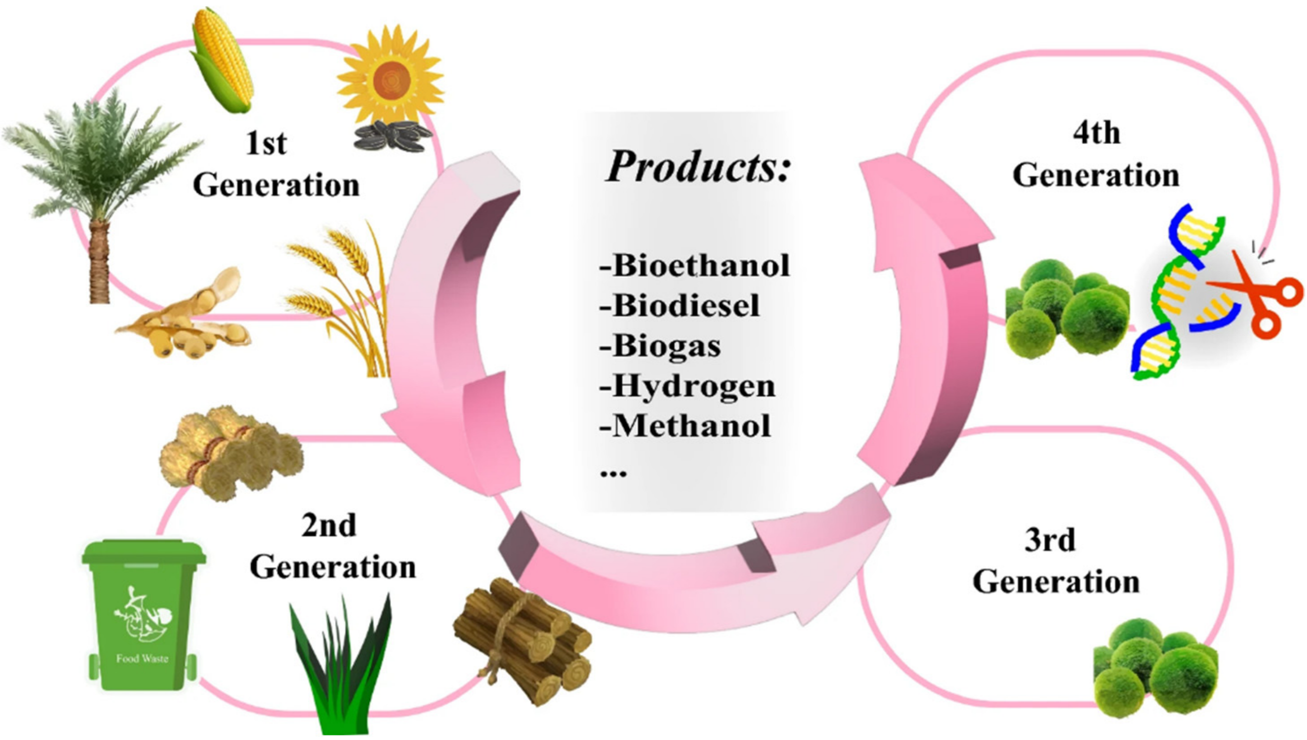

Figure 1. Changes in biofuels over time [15].

2. Things About Industrial Sludge and What It Is Made of

2.1. Types of Industrial Sludge

Industrial sludge is wastewater that originates from factories and other places where things are made. Many different types of trash are present. Before deciding whether different types of industrial sludge can be used to make biodiesel, we need to know what they are. This section discusses the following four main types of industrial sludge: different kinds of sludge, such as waste from cities, petrochemicals, the food industry, and the textile industry [16].

Municipal wastewater sludge, also known as sewage sludge, is a waste that remains after wastewater is treated in municipal treatment plants. Many organic and inorganic substances are removed when wastewater from homes and businesses is being processed. These include solids, organic matter, nutrients, pathogens, and trace pollutants [17–19].

Primary and secondary sludges are the two main types of sludge that originate from city wastewater. Sludge is formed when particles settle at the bottom during the first step of treatment. Meanwhile, biological solids are formed in the next step of treatment, which creates secondary sludge. It is easy to obtain this material, which contains significant amounts of organic matter, making it suitable for biodiesel production. Impure substances, however, make it harder to process and change.

Petrochemical sludge is produced when oil is refined and processed. It is then stored and used in power plants and refineries [20]. Heavy metals, hydrocarbons, catalyst remnants, and other impurities are often found in crude oil or petroleum feedstocks. Different refining methods and feedstock properties can significantly change the petrochemical sludge composition. Petrochemical sludge comes from refinery wastewater treatment units, tank bottoms, and oil–water separators. Advanced treatment methods must be used to produce biodiesel from petrochemical sludge, which is a complicated mix of organic and inorganic chemicals.

Organic waste, suspended solids, and waste from cleaning, preparing, and packing food produce sludge in the food processing industry. This type of sludge may contain lipids, triglycerides, amino acids, sugars, dietary fibers, food enhancers, additives, microbial biomass, and chemicals used to treat wastewater [21,22]. Many different types of sludges are used in the food industry. It is derived from making dairy products, processing fruits and vegetables, and making drinks. Biodiesel can be produced from sludge in the food industry, because it contains many lipids. However, dealing with pollutants, whose presence and makeup are difficult to predict, is important.

Sludge is left over after dyeing, printing, finishing, and washing the clothes. Wastewater from textile factories contains dye residues, chemical helpers, fibers, lint, and other particles that are either suspended or dissolved in it. Sludge is the word used for this purpose [23]. The textile industry creates sludge from synthetic colors, heavy metals, surfactants, and complex organic compounds. All these issues are difficult to treat and eliminate. It must be handled carefully to convert textile industry sludge into biodiesel because it contains pollutants that can harm the environment.

Individual types of industrial sludge are unique in their properties and makeup, and are difficult to handle and utilize. A deep understanding of the properties and makeup of these sludges is needed to find effective ways to handle, utilize, and transform them into valuable products such as biodiesel [24,25]. Developing new methods to treat industrial sludge as a renewable resource for biodiesel production is important.

As the biodiesel production process transitions from laboratory to industrial scale, several scalability challenges must be carefully managed to maintain efficiency and cost-effectiveness. One primary challenge is ensuring consistent mixing and uniform distribution of reactants in large reactors, which is critical for sustaining optimal reaction conditions. At larger scales, maintaining temperature control and minimizing energy consumption become increasingly complex, particularly in systems with high heat demands or complex configurations. Additionally, biological material stability can pose limitations, as prolonged processing times and increased material quantities may affect microbial viability or enzyme activity, potentially leading to decreased yields. Furthermore, the economic viability of biodiesel production at scale often depends on the cost-effectiveness of feedstock and process inputs. If the process cannot maintain high conversion rates or encounters elevated costs associated with large reactors or feedstock variability, it may face sustainability and profitability challenges. Addressing these limitations requires a focus on optimizing the reactor design, process parameters, and input materials, as well as evaluating the cost–benefit ratio to support sustainable industrial scaling.

2.2. Chemical and Physical Features

The chemical and physical properties of industrial sludge are important for determining whether it can be used as a raw material for biodiesel. High-quality biodiesel from sludge works differently, depending on its composition, contaminant levels, and lipid content.

The quality and amount of lipids: Examining the lipid content of industrial sludge provides insights into its fats, oils, and grease levels (FOGs). Lipids are the main ingredients used to make biodiesel because transesterification converts them into fatty acid methyl esters (FAMEs). Sludges with higher lipid contents are typically preferred for biodiesel production because they have a larger capacity to produce biofuels [26–29]. However, lipid quantity is not the sole determinant. The quality of these lipids, which encompasses their fatty acid content and unsaturation level, also has a crucial impact. These parameters influence the important characteristics of biodiesel, including cetane number, viscosity, and oxidative stability. Increased unsaturated fatty acids can enhance cold flow characteristics, but may also reduce oxidative stability.

Contaminants: Industrial sludge commonly harbors diverse pollutants that may harm both the biodiesel manufacturing processes and the ultimate quality of the product. Typical impurities include heavy metals, organic pollutants, water, suspended particles, and microbial infections [30]. When biodiesel conversion reactions do not work well, impurities can make the catalysts less effective and improve fuel properties. Heavy metals can affect the catalysts used in transesterification, making them toxic. Triglycerides can also be broken down by water, creating free fatty acids that can make the conversion process more difficult. For example, some pollutants can harm the environment and human health if not adequately dealt with during sludge treatment and biodiesel production processes.

Changes in composition: The ingredients in industrial sludge can vary depending on its origin and the methods used to make it. Sludge from the food, petrochemical, municipal wastewater, and textile industries is chemically and physically different. These differences occur because various businesses use different materials, production methods, wastewater treatment technologies, and rules and laws [31]. Typical petrochemical sludge includes heavy metals and hydrocarbons, whereas typical municipal wastewater sludge includes a large amount of organic matter with different amounts of pollution. Litter from the food business is full of proteins, fats, and organic wastes. Textile industry sludge, on the other hand, may have chemical companions and synthetic colors.

Understanding the reasons for variations in sludge composition is important for improving the efficiency of biodiesel production, customizing treatment methods, and maintaining the same quality of raw materials [32]. When sludge is first prepared for use in biodiesel, it may need to be cleaned or have its makeup changed.

Methods for analysis and process improvement: Researchers and professionals state that if the chemical and physical properties of industrial sludge are well-studied, they can be used as raw materials for producing biodiesel. This test involves finding pollutants, checking the sludge's lipid content, and obtaining a sense of its overall makeup. Advanced analytical methods, such as gas chromatography, mass spectrometry, and nuclear magnetic resonance spectroscopy, can be used to determine the lipid composition and identify any impurities that might be present.

Using this information, one can devise ways to improve processes and deal more effectively with problems, such as impurities and changes. Even if contaminants are present, new catalyst mixtures and reaction conditions can improve product quality and conversion efficiency. Improving sludge treatment technologies and developing new methods for separating and cleaning sludge can make it a better material for biodiesel production. Hence, long-lasting waste-to-energy choices can be created [33].

3. Systems and Techniques for Biodiesel Production

Figure 2 illustrates a process flow diagram depicting the generation of biodiesel from sewage sludge, emphasizing three distinct treatment pathways based on the sludge moisture content. The process commences with the pretreatment of sludge, which can be achieved through either dewatering or drying in three separate ways. The Lipid Extraction method, utilizing organic solvents or supercritical CO_2, has been employed for sludge containing no water. The process involves extracting lipids using an organic solvent or supercritical CO_2 and converting them into biodiesel through esterification or transesterification. The transesterification method can also be used for sludges that do not contain water. This approach combines transesterification with biodiesel extraction in a single step. The thermocatalytic reforming approach was employed for sludge with a water content of 30%. This technique entails thermocatalytic reforming, which enhances the quality of oil and facilitates biodiesel generation.

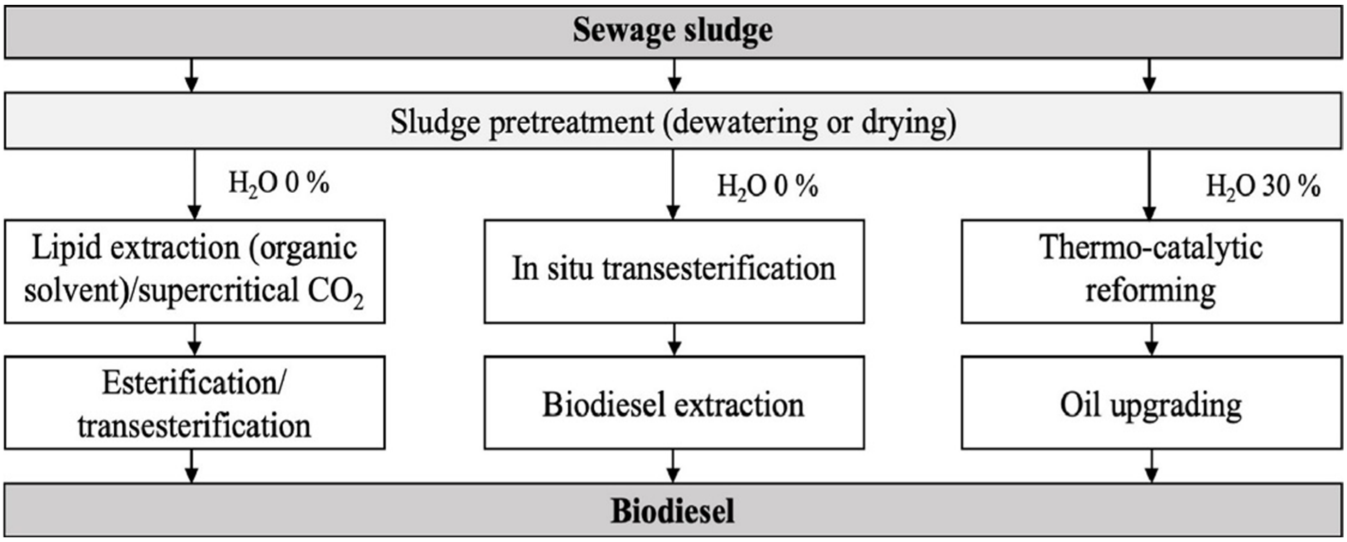

Figure 2. Biodiesel manufacturing from sewage sludge: Process flow diagram [16].

Every pretreatment technique offers distinct advantages and difficulties depending on the properties of the industrial sludge, intended results, and process specifications. Several pretreatment methods are required to maximize the effectiveness of lipid extraction, reduce energy usage, and improve the sustainability of biodiesel synthesis from industrial sludge [34,35].

Figure 3 thoroughly categorizes the pretreatment procedures for industrial sludge, including mechanical, thermal, chemical, biological, and physicochemical processes. Each category consists of distinct techniques that target the distinctive characteristics and difficulties associated with sludge in biodiesel production. Mechanical pre-treatment procedures, such as mechanical disintegration and ultrasonication, largely focus on physically breaking down the sludge structure to improve the release of lipids. However, these methods require a significant amount of energy. Thermal techniques such as hydrolysis and pyrolysis enhance the efficiency of lipid extraction and eliminate pathogens. Nevertheless, these techniques require substantial energy and can lead to corrosion problems in the processing machinery. Chemical pre-treatment techniques utilizing acids and bases are highly efficient in decomposing the intricate organic molecules present in sludge. Nevertheless, these approaches have the disadvantage of presenting difficulties in handling and disposing of chemicals owing to their caustic properties. Biological pretreatment methods utilize enzymatic hydrolysis with specialized enzymes, such as lipases or proteases. These processes provide a high level of specificity and can be performed under mild conditions. Although enzymes can be useful in some situations, their high cost and slow reaction rates can be problematic. Finally, physicochemical techniques such as supercritical fluid extraction and subcritical water treatment are effective and suitable for the environment. However, they require a lot of money and energy to be set up and run. The unique properties of the sludge, the desired results, and the overall goal of ensuring that the operation will be viable in the long term determine which pretreatment techniques are used and how they are mixed.

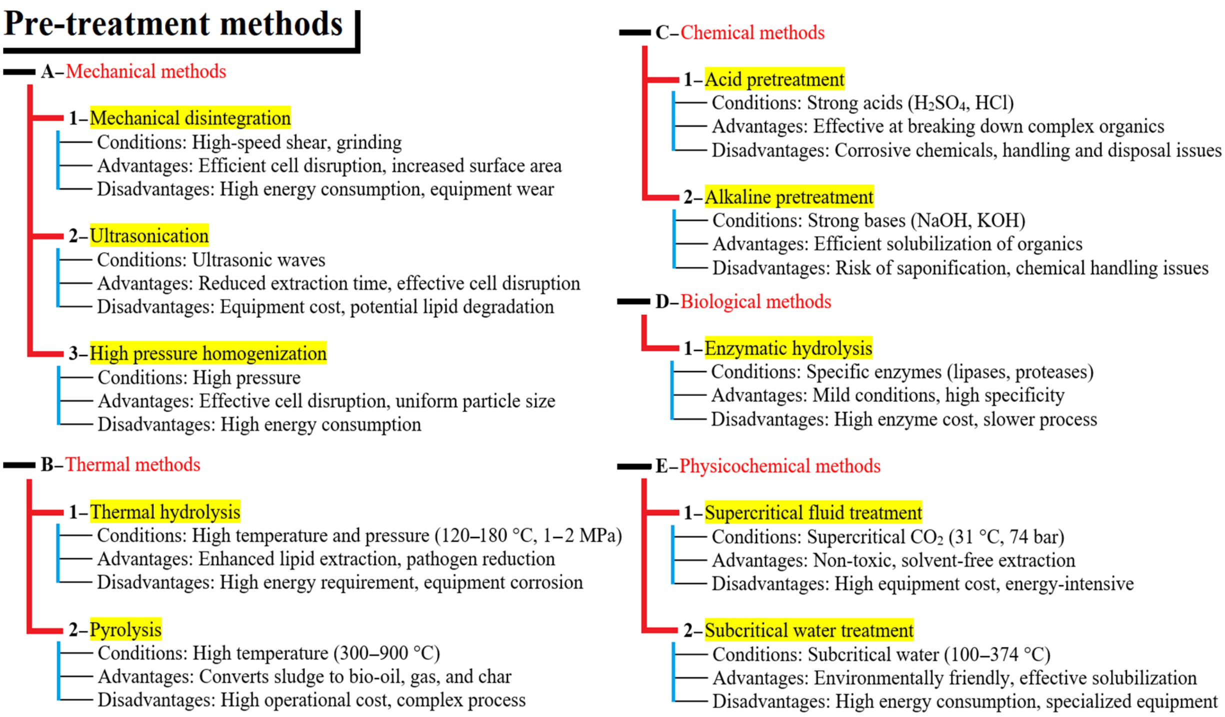

Figure 3. Grouping of pre-treatment methods for biodiesel production from industrial sludge.

3.1. Getting Industrial Sludge Ready for Use

An important part of biodiesel production is the pretreatment of industrial sludge. This is performed to make the process of lipid extraction and conversion more efficient, and to address problems that arise because of the way sludge is made [34,36]. This section explores a range of pretreatment procedures, including physical, chemical, and biological methods [37].

3.1.1. Physical Pretreatment

Physical pretreatment methods involve mechanical or thermal processes that aim to alter the physical properties of industrial sludge, making it easier to handle in the following processing stages. Some of the commonly used physical pretreatment treatments include the following:

- Drying: Moisture can be eliminated from sludge by employing evaporation or drying techniques such as air drying, solar drying, or mechanical dewatering. Drying significantly decreases the amount of sludge, boosts its manageability, and improves the effectiveness of lipid extraction [38].
- Grinding or milling: Grinding or milling of sludge particles mechanically reduces their size, increases the surface area, and improves their mixing with extraction solutions. This mechanism enhances the liberation of lipids from cellular structures, thereby increasing their availability during extraction.

3.1.2. Chemical Pretreatment

Chemical pretreatment procedures include the use of acids, bases, solvents, or other chemicals to shatter cell walls, dissolve lipids, and eliminate impurities from the industrial sludge. Conventional chemical pretreatment methods commonly used include the following:

- Acid/base treatment: Sludge is treated with acidic or alkaline solutions to hydrolyze the ester bonds in lipids. This process results in the breakdown of lipids into free fatty acids and glycerol [39–41]. Acidic conditions can assist in dissolving organic materials and forming inorganic solids, whereas alkaline conditions promote saponification reactions and the neutralization of acidic substances.

3.1.3. Biological Pretreatment

Biological pretreatment procedures utilize enzymes or microorganisms to decompose organic substances, disintegrate cellulosic materials, and improve the availability of lipids for extraction [42]. Typical biological pretreatment methods include the following:

- Enzymatic hydrolysis: Enzymes such as lipases or proteases facilitate the hydrolysis of ester bonds in lipids, converting lipids into free fatty acids and glycerol [43,44]. Compared with chemical techniques, enzymatic hydrolysis provides selectivity, efficiency, and mild reaction conditions, resulting in decreased energy usage and environmental effects.

3.2. Lipid Extraction Techniques

An important step in producing biodiesel is to obtain lipids from industrial sludge. This machine separates the important fats, oils, and greases (FOGs) into biodiesel. This section discusses the following three main ways to obtain lipids from a substance: mechanical extraction, solvent extraction, and supercritical fluid extraction.

Physical forces are used for mechanical extraction to separate lipids from the sludge matrix [45]. Pressure, centrifugation, and ultrasonication are some of the methods used in this study. These methods are described as follows:

- Pressing: Pressing the sludge with a hydraulic or screw press forces the lipids out of the system. This method is easy to use and does not harm the environment, but it might not extract as many lipids as other methods [46].
- Centrifugation: Centrifuges utilize strong rotational pressure to separate lipids according to variations in density. Although this approach effectively isolates unattached lipids, other steps are required to retrieve the lipids attached or linked to other substances [47].
- Ultrasonication: Ultrasound waves generate cavitation bubbles in sludge, which disturb cell walls and improve the release of lipids [48–50]. Although this technique enhances the effectiveness of extraction, it requires specialized equipment and can result in significant energy expenditure.

Solvent extraction utilizes organic solvents to dissolve and extract lipids from sludge, thereby providing high efficiency and scalability. Hexane, ethanol, and chloroform are the most frequently used solvents. These materials are described as follows:

- Hexane: Hexane, a non-polar solvent, efficiently dissolves lipids, which is why it is commonly used for lipid extraction [51–53]. The procedure involves combining sludge with hexane, which facilitates lipid dissolution. Subsequently, the solvent–lipid combination was separated from the solid residue. Despite its efficiency, hexane presents environmental and health hazards because of its instability and toxicity.
- Ethanol: Ethanol, a less hazardous and more ecologically sound substitute for hexane, can extract both polar and non-polar lipids. However, it may exhibit reduced efficiency when applied only to nonpolar lipid fractions. Ethanol extraction is preferred because of its reduced toxicity and convenient handling.
- Chloroform–methanol: Combining chloroform and methanol is a common way to separate lipids in a laboratory. Although it is possible to dissolve nonpolar lipids using chloroform, removing polar lipids using methanol is preferred. Unfortunately, this method uses smelly solvents, which makes it less suitable for large-scale operations.

As the name suggests, Supercritical Fluid Extraction (SFE) removes lipids from sludge using supercritical fluids, predominantly carbon dioxide (CO_2). Supercritical CO_2 is preferred because it can be used as a solvent in different ways, is non-toxic, and has little negative environmental impact.

- Supercritical CO_2 extraction: The CO_2 is heated and pressed until it reaches a state called "supercritical", which means that it is above its critical temperature and pressure. As CO_2 is in this state, it has the qualities of both liquid and gas. For example, it can dissolve objects and quickly spread out [54]. Lipids can be broken down by supercritical CO_2, which can effectively pass through the sludge matrices. The lipids can then be separated by lowering the pressure, which converts CO_2 back into gas [55]. Instead of leaving behind solvent residues, this method works very well and is environmentally safe. In any case, putting this project into action requires a large initial investment and ongoing costs, because it requires special tools.

- This depends on the properties of the industrial sludge, desired results, and process specifications, and each lipid extraction method has advantages and disadvantages. It is often necessary to combine different extraction methods to obtain the most lipids from industrial sludge, use less energy, and make the process more environmentally friendly.

Details of the mechanical, solvent, and supercritical fluid extraction methods used to separate lipids in biodiesel production are shown in Figure 4. The situations, benefits, and problems that arise with each methodology differ. It is possible to obtain lipids from the sludge matrix using mechanical extraction methods, such as pressing, centrifugation, and ultrasonication. There is no doubt that these methods are easy and environmentally friendly, but they might not always work and may require special tools and energy. Many solvent extraction methods work well and can be scaled up. These include hexane, ethanol, and mixtures of chloroform and methanol. Hexane works very well, but can also harm people and the environment. Ethanol, which is safer and better for the environment, might not work for nonpolar lipid fractions. Because dangerous solvents are used, the chloroform–methanol method is less effective for large-scale operations. However, it works well in the laboratory. Supercritical CO_2 extraction (SFE) is a useful and environmentally friendly method that does not require any solvent. However, because of the need for specialized equipment, putting this project into action requires much money upfront and regularly. The needs of the biodiesel production process, including the goals for lipid output, properties of the industrial sludge, and environmental factors that need to be considered, determine the lipid extraction method.

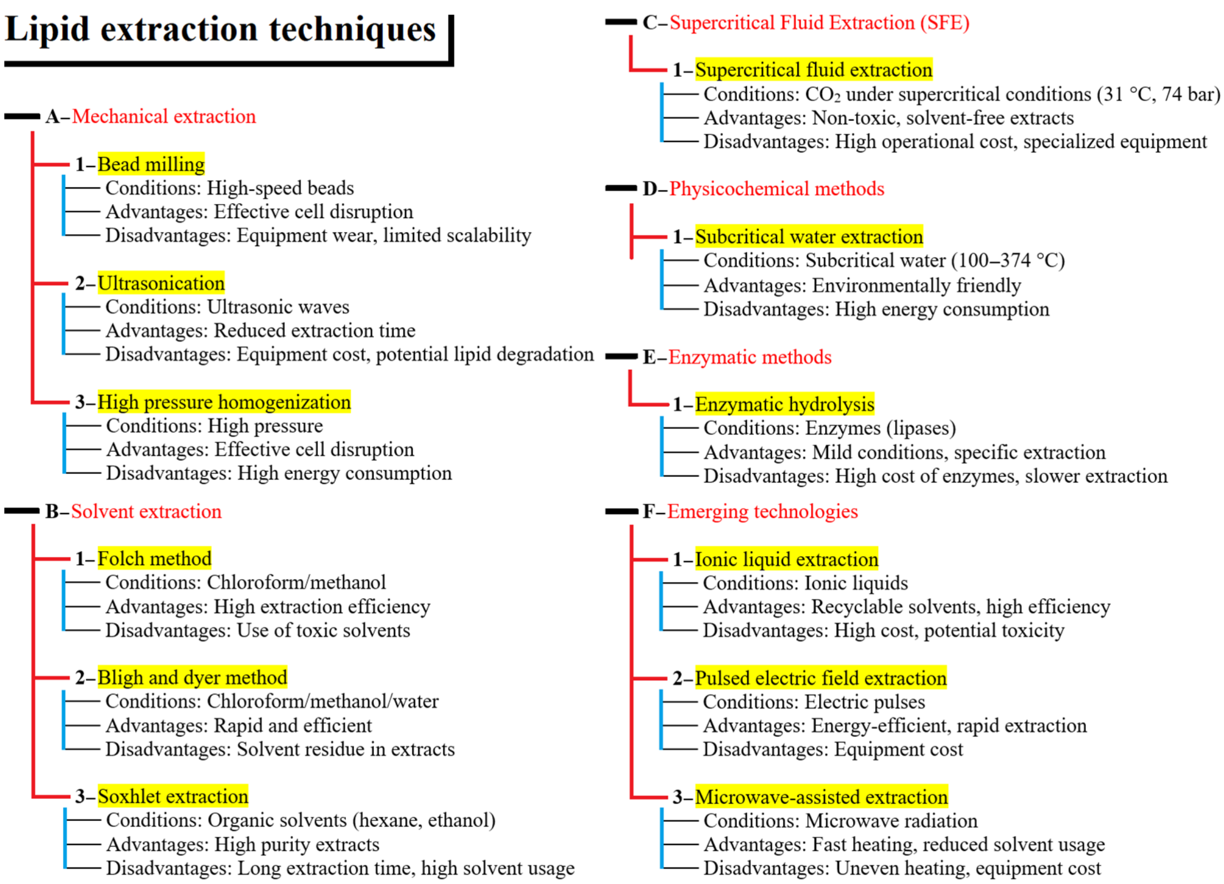

Figure 4. Grouping of methods for lipid extraction for biodiesel production.

3.3. Transesterification Processes

A key chemical step in biodiesel production is transesterification, which converts triglycerides into fatty acid methyl esters (FAMEs), which are the main ingredients of biodiesel [56]. There are the following three main types of transesterification: base-catalyzed transesterification, acid-catalyzed transesterification, and enzyme-catalyzed transesterification.

- Base-catalyzed transesterification: Base-catalyzed transesterification is a common method for producing biodiesel because it offers significant benefits in terms of reaction speed and efficiency [57]. When triglycerides and methanol react, the basic catalyst is usually sodium hydroxide (NaOH) or potassium hydroxide (KOH), which helps the reaction occur. The catalyst starts to remove a proton from methanol, which causes the formation of methoxide ions. After interacting with the carbonyl carbon of triglycerides, these ions create FAMEs (fatty acid methyl esters) and glycerol. Fast response times and high conversion rates at relatively low temperatures and pressures make this method cost-effective and suitable for feedstocks with low free fatty acid (FFA) content [6,58,59]. However, the water and free fatty acids (FFAs) in the raw material can affect the base-catalyzed transesterification process. These changes could lead to the creation of soap and a decrease in biodiesel production. Therefore, pretreatment steps are often required to remove water and FFAs.
- Acid-catalyzed transesterification: Acid-catalyzed transesterification uses sulfuric acid (H_2SO_4) or hydrochloric acid (HCl) as a catalyst to accelerate the hydrogenation reaction [60,61]. Because the acid catalyst adds a proton to the oxygen atom of the carbonyl group in triglycerides, the carbonyl carbon becomes more electrophilic, and methanol is more likely to attack it. This reaction generates glycerol and fatty acid methyl esters (FAMEs). Large amounts of free fatty acids (FFAs) in feedstocks work well with acid catalysis because they can convert FFAs into esters and triglycerides into other compounds without any other treatment. However, the rate of transesterification sped up by acid is lower than that sped up by base, and higher temperatures and longer reaction times are required. Furthermore, acid catalysts are corrosive; therefore, equipment that is resistant to corrosion must be used. This means that the overall operational cost increases.
- Enzyme-catalyzed transesterification: Liposomal lipase enzymes help convert triglycerides into FAMEs during enzyme-catalyzed transesterification [62]. Lipase enzymes break down triglycerides into free fatty acids, diglycerides, and monoglycerides. After esterification with methanol, these products formed FAMEs. When enzymes are used to speed up reactions, they work best at room temperature and pressure, are highly specific, and produce fewer waste products. They are also resistant to water and free fatty acids (FFAs); therefore, they do not need to be treated first. However, enzymes are expensive, which increases the overall cost of production. Additionally, excessive methanol and glycerol can stop the enzymes from working; therefore, the reaction conditions must be carefully adjusted. Research is being conducted to find ways to immobilize and recycle enzymes using this method more often and for less money. Recent progress in the use of nanostructured catalysts has demonstrated the potential to improve the efficiency of enzyme-catalyzed transesterification, resulting in greater selectivity and gentler reaction conditions [63].

Some transesterification methods are better than others, depending on the feedstock, end goal, and process requirements. When choosing a transesterification method, it is important to consider the duration of the reaction, the temperature at which it occurs, the catalyst costs, and if any pre-treatment is needed to make biodiesel that works well and lasts a long time.

By converting triglycerides into fatty acid methyl esters (FAMEs), transesterification methods are very important for producing biodiesel. Figure 5 shows that the three types of transesterifications—base-catalyzed, acid-catalyzed, and enzyme-catalyzed—each have advantages and disadvantages. Base-catalyzed transesterification is often used because it works very well and is inexpensive. Despite this, feedstocks need low free fatty acids (FFA), so soap does not form. Because it does not need to be treated first, transesterification with acid is a good choice for feedstocks with many free fatty acids (FFA). However, this method has some problems such as slower reaction rates and conditions that are detrimental to metals. The reaction conditions are suitable for enzyme-catalyzed transesterification and can be very selective. However, it runs into problems with expensive enzymes and the blocking effects of high levels of methanol and glycerol. The best transesterification method was chosen based on factors such as feedstock properties, reaction speed, and cost of running the process. Adding pretreatment steps and finding the best reaction conditions can make biodiesel production more efficient and long-lasting.

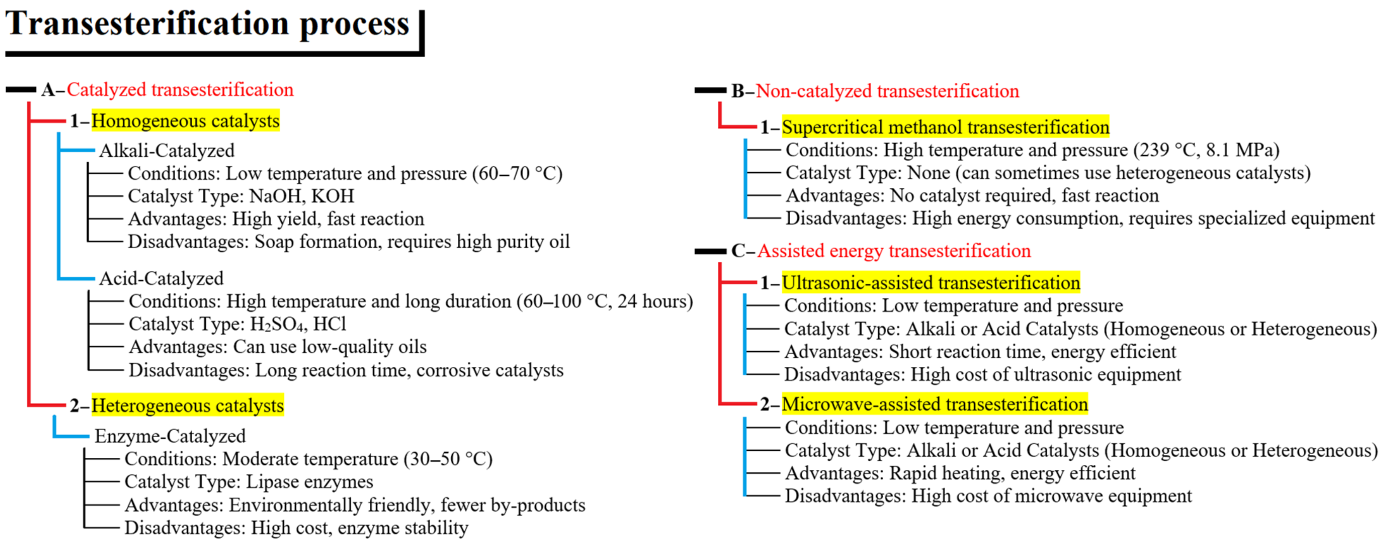

Figure 5. Sorting transesterification processes for producing biodiesel into groups.

Table 1 lists the advantages and disadvantages of the different types of catalysts used in the transesterification process for producing biodiesel. It is best to use homogeneous catalysts, such as sodium hydroxide and potassium hydroxide, because they speed up reactions, increase conversion rates, and show better selectivity. They operate under less harsh reaction conditions and can be changed to operate with different feedstocks. However, these catalysts tend to dissolve into biodiesel, do not last long, can be used more than once, and can be damaged by contaminants in the feedstock [64–66]. On the other hand, differentiated catalysts are easy to separate from the reaction mixture, which makes it easier to get the catalyst back and use it again. Their tolerance for contaminants in the feedstock is high, and they help the environment by reducing waste to a minimum. However, heterogeneous catalysts have problems such as limited mass transfer, chance of deactivation, complicated preparation methods, and limited selectivity [64,67,68]. Because of their gentle reaction conditions, high specificity and selectivity, and ability to handle contaminants well, enzyme-based catalysts are an environmentally friendly choice. As biocatalysts, these substances can break down naturally and can be used again. However, enzymes are costly, easily damaged by reaction conditions, do not last long when used, and take a long time to react [69,70].

Table 1. There are advantages and disadvantages to using different catalysts in the transesterification process.

Catalyst Type	Pros	Cons	References
Homogeneous	Faster reaction rates and higher conversion yields; Greater selectivity; Versatility and adaptability to various feedstocks; Operate under milder reaction conditions	Potential for leaching into the biodiesel product; Limited stability and reusability; Sensitivity to impurities	[64–66]
Heterogeneous	Easy separation; Catalyst reusability; Tolerance to impurities; Environmental sustainability	Mass transfer limitations; Catalyst deactivation; Complex catalyst preparation; Limited selectivity	[64,67,68]
Enzymatic	Mild reaction conditions; High specificity and selectivity; Tolerance to impurities; Biodegradability and environmental sustainability; Catalyst reusability	Higher cost; Sensitivity to reaction conditions; Limited operational stability; Longer reaction times	[69,70]

Recent progress in the search for new biofuel sources has been encouraging, especially regarding alternative energy sources that are not yet well known. One example is the study of bitter orange oil from Petitgrain as a renewable energy source. In this study, the shape of the piston bowl and the pressure at which the fuel was injected were changed. The results showed that the engine efficiency and emission properties were significantly improved [71]. This study demonstrates how non-traditional sources of waste can be used to produce biofuels. It also stresses the importance of conducting more studies and improving the use of these raw materials in sustainable energy projects.

3.4. Innovative Methods

Researchers are exploring novel transesterification techniques that can enhance the reaction rates and reduce the energy requirements in the pursuit of more efficient and sustainable biodiesel production. This section focuses on the following two promising methods: microwave-assisted and ultrasound-assisted transesterification.

- Microwave-assisted transesterification: Microwave-assisted transesterification uses microwave radiation to heat objects quickly and evenly, which greatly accelerates the reaction. When microwaves interact with polar molecules, such as triglycerides and methanol, they cause rotational motion and heat to be produced through dielectric heating. The direct heating method accelerates the reaction by evenly spreading the energy and lowering the energy required to initiate the reaction. Compared to traditional heating methods, microwave-assisted transesterification significantly reduces the reaction time and energy use by a large amount. Because this technique heats everything evenly and transfers energy efficiently, it makes it easier to control reactions and produce more biodiesel. However, using microwaves to help with procedures requires special tools, which can increase the initial setup costs. Furthermore, making microwave reactors sufficiently large to produce biodiesel on a large scale remains a challenge. This is because the reaction parameters must be fine-tuned to avoid overheating and obtain reliable results. Despite these problems, microwave-assisted transesterification is promising for efficient and long-lasting biodiesel production.
- Ultrasound-assisted transesterification: In ultrasound-assisted transesterification, high-frequency sound waves help the reaction proceed faster. Ultrasound waves cause cavitation bubbles to form within the reaction mixture. These bubbles collapse, creating areas of high temperature and pressure. This effect accelerates a chemical reaction called transesterification, which strengthens the movement of substances. Ultrasound-assisted transesterification accelerates reactions and increases yields by better mixing and spreading of reactants, shortening reaction times, and possibly lowering the required concentration of inhibitors. The high quality of the biodiesel produced was also maintained because this method allows for gentle reaction conditions. Specialized

equipment is needed to use ultrasound, and the frequency and strength of the waves must be carefully controlled to avoid putting too much energy into biodiesel and lowering its quality. In addition, more research needs to be conducted on the scalability and profitability of large-scale industrial manufacturing.

These advanced transesterification methods, microwave- and ultrasound-assisted, demonstrate significant improvements in response time, energy efficiency, and biodiesel output. However, practical challenges, including high equipment costs and scaling limitations, must be addressed for these techniques to be viable for industrial biodiesel production.

3.5. Nanocatalysts in Biodiesel Production

Biodiesel production has been carefully studied to determine how nanocatalysts can be used. They make the reactions more efficient and lower the high-energy inputs required in transesterification processes [72]. The response time, energy efficiency, and biodiesel output were improved by microwave- and ultrasound-assisted transesterification. However, these techniques can only be used effectively in industry if the equipment costs, inability to scale up the process, and inability to find the best reaction conditions can all be overcome. Continuous research and progress in these areas is needed to fully utilize innovative transesterification processes for biodiesel production.

Table 2 shows the range of nanocatalysts employed in biodiesel synthesis, emphasizing the specific experimental parameters, biodiesel yields, and pertinent research. Nanocatalysts have attracted considerable interest for biodiesel production because of their improved catalytic characteristics, leading to increased biodiesel yields and more effective reaction conditions. For example, waste cooking oil was treated with nano-CaO at 60 °C for 2 h using a molar ratio of 12:1 and a catalyst loading of 2.5%. This process resulted in a biodiesel yield of 94% [73]. Similarly, the combination of sodium oxide and carbon nanotubes (CNTs) yielded an impressive yield of 97% when subjected to slightly varied circumstances [74]. Novel methods, such as using graphene oxide in conjunction with bimetal zirconium/strontium oxide nanoparticles, exhibit remarkable effectiveness by attaining 91% output from utilized cooking oil at 120 °C for 1.5 h. This was accomplished with an exceptionally minimal catalyst quantity of 0.5% [75]. This suggests a decrease in the quantity of catalyst used without sacrificing the production output. Microwave- and ultrasound-assisted transesterification technologies have excellent response times, energy efficiencies, and biodiesel outputs. However, for these techniques to be useful in industry, they need to be able to solve past problems, such as the high cost of the equipment, the inability to scale up the process, and the need to find the best reaction conditions. Research and development must continue in these areas to get the most out of these cutting-edge transesterification processes for biodiesel production [76]. Although the conditions were not as harsh, using nano-CaO yielded 96% yield when the old frying oil was processed [77]. This table shows how the bifunctional and magnetically recoverable nanocatalysts were used. One example is the bifunctional magnetic nanocatalyst, which achieves the best yield of 98.2% from used cooking oil [78]. These catalysts can be easily recycled, which makes the biodiesel production process more cost-effective. Therefore, the use of nanocatalysts to produce biodiesel has many benefits, including better catalytic activity, shorter reaction times, and less environmental damage, because they can be reused and require less catalyst. Selecting the right nanocatalyst and experimental settings for the feedstock and the desired results are vital for obtaining the highest biodiesel production and ensuring that the process lasts.

Table 2. Different nanocatalysts were used to prepare biodiesel.

Feedstock	Catalyst	Experimental Conditions (Temperature (°C)/M Molar Ratio/Catalyst (wt.%)/Time (h))	Biodiesel Yield (%)	References
Waste cooking oil	Nano CaO	60 °C/12:1/2.5%/2 h	94	[73]
Waste cooking oil	Sodium oxide impregnated on carbon nanotubes (CNTs)	65 °C/20:1/3%/3 h	97	[74]
Used cooking oil	Graphene oxide and bimetal zirconium/strontium oxide nanoparticles	120 °C/4:1/0.5%/1.5 h	91	[75]
Used frying oil	Nano CaO	50 °C/8:1/1%/1.5 h	96	[77]
Used frying oil	Nano MgO	65 °C/24:1/2%/1 h	93.3	[79]
Sunflower oil	$MgO/MgAl_2O_4$ nano-catalyst	110 °C/12:1/3%/3 h	95.7	[76]
Sunflower oil	$Cs/Al/Fe_3O_4$ nano-catalyst	58 °C/12:1/1%/2 h	94.8	[80]
Chicken fat	$CaO/CuFe_2O_4$	70 °C/15:1/3%/4 h	94.52	[81]
Waste cooking oil	ZnCuO/N-doped graphene (NDG)	180 °C/15:1/10%/8 h	97.1	[82]
Olive oil	Magnetite nanoparticle-immobilized lipase	37 °C/12:1/1%/1 h	45	[83]
Microalgae oil	Fe_3O_4/ZnMg(Al)O solid	65 °C/12:1/3%/3 h	94	[84]
Olive oil	MgO nanoparticles	60 °C/10:1/2%/2 h	80	[85]
Tannery waste	Cs_2O loaded onto a nano-magnetic core	65 °C/21:1/7%/5 h	97.1	[86]
Used cooking oil	Bifunctional magnetic nanocatalyst	65 °C/12:1/4%/2 h	98.2	[78]

In conclusion, nanocatalysts present significant opportunities for advancing biodiesel production by improving catalytic activity, shortening reaction times, and lowering environmental impact. However, selecting an appropriate nanocatalyst and optimizing the reaction conditions are essential to achieve high yields and sustainable biodiesel production. Continued research into scalable, cost-effective nanocatalyst systems is required to maximize the benefits of these innovative catalytic materials.

4. New Developments in Making Biodiesel from Industrial Waste

4.1. Case Studies and Pilot Projects

Several case studies and pilot projects have recently shown the extent to which biodiesel has been produced from industrial sludge. This section examines the following important research projects in detail, including how they were conducted, what they found, and how they changed the field:

- Conversion of municipal wastewater sludge into biodiesel: A European research program investigated whether it could convert sludge from city wastewater treatment plants into biodiesel. Before lipid extraction using hexane as a solvent, the sludge was dried and ground as part of the pre-treatment process. Biodiesel was prepared from lipids obtained by treating them with base-catalyzed transesterification. The study showed that 80% of the lipids could be removed. This means that the total amount of lipids removed could be used to make approximately 70% of biodiesel. According to the European quality standards (EN 14214), the biodiesel produced was good. This implies that water from cities can be used to produce biodiesel.
- Utilization of petrochemical sludge for biodiesel production: Asian experts examined the idea of petrochemical sludge being used to produce biodiesel. Before treatment, acid hydrolysis was used to break down the complex hydrocarbons in the sludge and free any trapped lipids. First, supercritical CO_2 was used to remove the lipids from the mixture. Subsequently, acid-catalyzed transesterification occurred. The research obtained a lipid extraction efficiency of 75%, which led to a biodiesel production rate of 65% using the extracted lipids [87]. Highly refined biodiesel with a low sulfur content was prepared. This makes it suitable for mixing with diesel fuel. In this study,

we investigated the potential of petrochemical sludge as an essential raw material for biodiesel production.

- Conversion of food industry sludge to biodiesel: The U.S. pilot projects are currently trying to convert waste from the food industry into biodiesel. Following enzymatic hydrolysis to release lipids, ultrasound-assisted transesterification was used to accelerate the reaction and increase the yield. The project recorded an extraction efficiency of 85% for lipids and biodiesel production efficiency of 75%. According to ASTM D6751, the biodiesel produced met the quality standards for fuel. Additionally, this study focused on the advantages of combining enzymatic and ultrasound-assisted methods to make biodiesel production from food industry waste more efficient and long-lasting.
- Conversion of textile industry sludge to biodiesel: As part of a pilot project in South Asia, the transformation of textile industry waste sludge into biodiesel was examined. The sludge was first treated by drying and grinding with a microwave. Ethanol was then used to extract fats. Both bases and enzymes were used to accelerate the transesterification process. This study achieved a lipid extraction efficiency of 78%, leading to a biodiesel output of 68%. The biodiesel produced was relatively thin and had high resistance to oxidation, which meant that it met the global standards for biodiesel. This study showed that it is possible to make biodiesel from textile industry waste using cutting-edge pretreatment and transesterification methods.

These case studies and pilot projects show how far we have come to use different kinds of industrial sludge to produce biodiesel. They demonstrate many approaches and positive results in various areas and industries.

4.2. Technological Advancements

Owing to this new technology, the production of biodiesel from industrial sludge is now much easier and more effective. This section discusses the following two areas in which progress has been made: better extraction and more advanced transesterification methods.

4.2.1. Advanced Extraction Methods

Microwave-assisted extraction is a well-known and effective method for obtaining lipids from industrial sludges. Microwaves, which break down cell walls and allow lipids to escape, are used in this method to heat objects quickly and evenly. It takes much less time and energy to use microwave-assisted extraction than other methods. Improved process control is another benefit of this method. This means that more lipids are produced, and separation works better.

In ultrasound-assisted extraction, high-frequency sound waves generate cavitation bubbles in the sludge matrix. It is easier for the mass to move and the lipids to be released when these bubbles pop. This is because they create places with high temperatures and pressure. With this method, both extractions work better, and the working time is reduced. Therefore, it uses less solvent and can be used in mild weather, making it a good choice for the earth. Ultrasound-assisted extraction is the most effective method to obtain authoritarian sludge structures. Other methods may also not work in these cases.

In supercritical fluid extraction (SFE), supercritical CO_2 is used to remove lipids from the sludge. Because CO_2 is a unique solvent in its supercritical state, it can easily enter the sludge matrix and break down the lipids. We obtained very clean lipids from SFE because it works well for extraction. As SFE is environmentally friendly, it leaves almost no carbon dioxide (CO_2) behind, as CO_2 is not harmful and can be easily removed from the recovered lipids. Using this method, dangerous organic solvents are not required.

4.2.2. Better Processes for Transesterification

The development of heterogeneous catalysts has significantly improved the transesterification process. Conversely, differential catalysts are easier to separate from the reaction mixture than homogeneous catalysts; therefore, they do not require as many complicated purification steps. This makes it easier to reuse and stabilize the catalysts, which lowers operational costs [88]. Heterogeneous catalysts also reduce the development of soap and enhance biodiesel yield and quality. Recently, many studies have focused on developing more active and selective catalysts.

Enzyme-catalyzed transesterification utilizes lipases to facilitate the transformation of triglycerides into fatty acid methyl esters (FAMEs). Progress in enzyme technology has led to the development of stronger and more effective enzymes for the manufacture of biodiesel. Enzyme-catalyzed processes function at low temperatures and pressures, resulting in lower energy usage and the maintenance of biodiesel quality. In addition, they are less sensitive to water and free fatty acids, meaning that the feedstock does not need to be treated. This process is now more economically viable because of the immobilization and enzyme-recycling techniques.

Reactive distillation includes transesterification and separation. This method improves the efficiency and conversion rates of the transesterification process. The number of steps and pieces of equipment needed for reactive distillation is kept to a minimum, thereby lowering both the initial investment and ongoing costs. In addition, it accelerates the reactions and improves the final product by constantly eliminating any unwanted substances produced during the process.

These scientific discoveries have shown that biodiesel production from industrial waste has come far away. They show new ideas that make things more efficient, cut costs, and have less effect on the environment.

4.3. Economic Viability

It is important to determine whether biodiesel production from industrial waste is financially viable as a long-term alternative to regular biodiesel. This section analyzes the full cost of producing biodiesel from sludge compared with that of more traditional methods.

Compared to common feedstocks, such as vegetable oils or animal fats [4], industrial sludge is usually seen as an unwanted byproduct that is cheaper or even not economically viable. Many industries spend a lot of money to get rid of sludge, but these businesses can save money by turning sludge into biodiesel. This makes biodiesel production more economically appealing by lowering the cost of raw materials using sludge as a feedstock. The production of biodiesel from industrial sludge is more cost-effective than that from traditional feedstocks. Studies suggest that feedstock costs alone can account for up to 70–80% of biodiesel production costs when vegetable oils or animal fats are used as sources [65]. For example, soybean oil biodiesel production typically ranges from USD 0.60 to 0.80 per liter [89], while animal fat-based biodiesel costs are approximately USD 0.50 to 0.70 per liter [90]. In contrast, industrial sludge, often obtained at little to no cost, can reduce overall production expenses by 30–40%, thus lowering the biodiesel cost to approximately USD 0.30 to 0.50 per liter [91]. Moreover, pre-treatment costs, including drying, grinding, and chemical or biological treatments, add approximately USD 0.05 to 0.15 per liter, depending on the technology choice. Recent advancements, such as microwave- and ultrasound-assisted extraction, require initial investments of approximately USD 50,000–200,000 in specialized equipment, but can reduce energy use by 15–20%, potentially saving USD 0.02 to 0.04 per liter in energy costs [92]. Transesterification, one of the primary cost drivers, varies based on the choice of the catalyst. Enzyme-based processes are initially more expensive, at approximately USD 0.10–0.15 per liter but offer long-term savings due to reusability. Additionally, energy expenses account for approximately 10–15% of the total costs, with optimized methods such as microwave extraction capable of reducing energy demand by nearly 20%, translating to savings of USD 0.05–0.10 per liter [93]. Furthermore, businesses benefit from lower waste disposal costs and the opportunity to make money by selling biodiesel.

Things such as drying, grinding, and adding chemical or biological treatments to the sludge are needed before it can be used to produce biodiesel. However, these operations incur costs that are added to the overall production cost. In the meantime, improvements in pretreatment technology are meant to lower these costs. For example, making microwave- and ultrasound-assisted extractions more successful and less expensive may require larger investments in specialized equipment. Overall, these methods offer long-lasting economic benefits by increasing efficiency and shortening processing time.

Using different methods can change the cost of lipid extraction and transesterification. Although new methods such as microwave- and ultrasound-assisted extraction might work better, they might be more costly for the special tools they need. Transesterification uses enzymes and catalysts, the prices of which change over time. Compared to other methods, heterogeneous catalysts and enzyme-catalyzed processes may be more expensive at first, but they save money in the long run because they can be reused and produce fewer waste products.

Most of the overall cost of making biodiesel comes from the energy used. Minimizing operational costs can be achieved with energy-saving techniques such as microwave and ultrasound-assisted methods. Maintenance of the equipment on a regular basis and the presence of highly experienced workers are also necessary to ensure smooth operation. Innovative solutions that automate processes and reduce the need for human involvement can effectively lower these costs, thus making the project more economically viable.

It is common for feedstocks, such as soybean oil, rapeseed oil, and palm oil, to change prices, which affects traditional biodiesel production. Potentially, these raw materials make up a large part of the total production cost. Alternatively, industrial sludge is a reliable and possibly abundant source of raw materials, especially if many industries continue to waste it. Consistency can make the production costs easier to predict, which is an advantage over other biodiesel sources.

Utilizing industrial sludge for the creation of biodiesel not only lowers the cost of raw materials but also has significant environmental benefits. This process promotes environmental sustainability as it keeps trash out of landfills and reduces greenhouse gas emissions related to the removal of sludge. The overall economic viability of producing biodiesel from sludge is improved by lower feedstock costs and cleaner waste disposal. In addition, businesses can make money by selling their waste, which adds to their income. While the initial cost of buying specialized equipment and advanced technologies for producing biodiesel from sludge may be higher, the long-term cost savings and environmental benefits may be greater. As technology improves and grows, the cost of producing biodiesel from sludge is expected to decrease. Compared to regular biodiesel, this makes biodiesel more competitive.

Studies have shown that producing biodiesel from waste materials such as industrial sludge is potentially profitable because it saves a lot of money and has a smaller impact on the environment [94]. In Table 3, the text talks about the pros and cons of various biodiesel feedstocks are discussed, focusing on the complex factors that need to be considered when selecting the appropriate raw materials for biodiesel production. Waste cooking oil is useful because it can be used to generate more energy sources, reduce waste, and lower the carbon footprint. It is also cost-effective and environmentally friendly; therefore, it is easy to add to the infrastructure that is already in place for making biodiesel. Nevertheless, difficulties of considerable magnitude arise from factors such as the quality and consistency of feedstock, removal of contaminants, and restricted availability and challenges associated with storage. Owing to fluctuations in the composition of waste cooking oil, it is necessary to have strong pre-treatment processes in place to guarantee a constant quality of biodiesel [95–97]. Animal fats discarded as trash have a significant amount of energy and can be efficiently used to manage waste. They serve as sustainable and economically viable sources of biodiesel. In addition, they play an important role in achieving carbon neutrality. Nevertheless, these raw materials encounter difficulties associated with fluctuations in quality, limited accessibility, and rivalry with other sectors. The broad adoption of any new process can be significantly influenced by regulatory compliance [98–100]. Algae are an appealing source of raw material because they grow quickly, produce a large amount of oil, and can capture carbon dioxide. Algae may grow in several environments, making them a versatile choice. Although there are benefits to producing algal biodiesel, it requires the use of sophisticated technologies and involves significant extraction expenses. The vulnerability of algae to contamination adds an additional layer of complexity to their widespread utilization [101,102]. Municipal sewage sludge offers a plentiful source of material that can aid in decreasing reliance on fossil fuels while also supporting the recycling of nutrients and the potential for carbon neutrality. Nevertheless, diverse mixtures of sewage sludge, elevated moisture content, and levels of contaminants pose considerable difficulties. For techno-economic feasibility, it is also necessary to deal with these problems using advanced processing and treatment methods [103–109]. In conclusion, selecting the feedstock for biodiesel production requires careful analysis of the advantages and disadvantages of each option. To develop biodiesel production methods that work and last, one needs to carefully consider and weigh things such as the cost and supply of feedstock, the amount of processing that needs to be performed, and the impact on the environment.

Table 3. Pros and cons of different feedstocks for biofuels.

Parameter	Advantages	Challenges	References
Waste cooking oil	Diversifies energy sources, reduces waste, renewable and sustainable, cost-effective, lower carbon footprint, job creation, compatible with existing infrastructure.	Quality and consistency issues, contaminant removal, limited availability, competition with other applications, storage and handling issues, feedstock variability, and regulatory compliance.	[95–97,110–117]
Waste animal fats	Renewable and sustainable, cost-effective, high-energy content, positive fuel characteristics, effective waste management, carbon neutrality.	Quality variability, restricted availability, regulatory compliance, and competition with other industries.	[98–100,118–122]
Algae	Adaptable to various habitats, rapid growth rates, high oil yield, and carbon dioxide sequestration.	Requires advanced technologies, susceptibility to contamination, and high extraction costs.	[101,102,123,124]
Municipal Sewage Sludge	Waste utilization, abundant feedstock, reduce fossil fuel dependency, nutrient recycling, and potential carbon neutrality.	Heterogeneous composition, high moisture content, high contaminant levels, nutrient imbalance, and techno-economic feasibility.	[36,103–109]

5. Problems with Using Processed Industrial Waste to Make Biodiesel

5.1. Technical Challenges

The conversion of industrial sludge to biodiesel presents significant technical challenges that must be addressed to make the process efficient, cost-effective, and environmentally sustainable. The primary technical challenges involve variability in sludge composition and optimization of lipid extraction and conversion processes.

Industrial sludge is composed of a complex and heterogeneous mixture of materials, and its composition varies depending on the source and the industrial processes involved. This variability introduces the following challenges:

- Lipid content variability: Differences can be seen in the fatty makeup of the industrial sludge. Compared to sludge from cloth or municipal sources, sludge from food processing businesses usually contains more lipids. Consistency problems directly affect the overall output and cost viability of biodiesel production, making these issues a very important problem that needs to be addressed [125]. Industrial sludge, which is similar to municipal solid waste (MSW), is sometimes considered a garbage product that does not have much value and can be used repeatedly. Using these feedstocks not only lowers the costs of eliminating trash, but also helps the environment by reducing the use of fossil fuels. New studies have examined different setups of MSW-based integrated gasification combined cycle (IGCC) systems, focusing on how they can produce chemicals and power. For example, Wu et al. [126] used municipal solid waste (MSW) as a source of I systems and discussed three different ideas. Each plan uses new methods such as calcium looping gasification to make the process more effective and long-lasting. These designs show how waste-to-energy methods can be combined with modern chemical syntheses. They also taught us how similar methods could be used to produce biodiesel from industrial sludges. With this integration, the goal is to increase the yield and reduce carbon pollution.

- Contaminants: Many harmful chemicals, heavy metals, organic toxins, and other impurities can be found in industrial sludges. These impurities can make it harder to extract and change lipids, which could lower the quality of biodiesel and make it more expensive to make because more cleaning and trash disposal are needed.
- Complex matrix: The complex makeup of industrial sludge, which includes proteins, carbohydrates, and inorganic substances, makes it difficult to separate lipids. Additionally, these parts require additional pretreatment steps, which increases the difficulty and cost of biodiesel production.

The success of the process depends on how well the lipids are removed from the industrial sludge and converted into biofuels. Ganesan et al. [127] used advanced fuel injection methods, such as combining split injection with reactivity-controlled compression ignition (RCCI) dual-fuel combustion, to make biodiesel engines much more efficient and reduce pollution. Creative ways to burn substances and different biofuels can be used to create better and more efficient energy sources, as shown by the progress made. Therefore, biodiesel made from factory waste is an even better choice for current engines. As thermochemical conversion technologies improve, they have also shown that sewer sludge can be used to make green energy by being gasified. Viswanathan et al. [128] investigated how sewer sludge can be converted into syngas using a downdraft gasifier. The best syngas was produced using a modelling approach that combined the thermal equilibrium and kinetic models. Changing the working conditions, such as the flow rates of fuel and gasifying agents, as well as the temperature and pressure inside the gasifier, has a significant effect on the syngas composition and how well they turn cold gas into syngas. These results show that response surface methodology (RSM) can be used to improve the efficiency and scalability of the energy output from sludge by determining the optimal operating conditions. Thus, it is more likely that these technologies will be used to produce biofuels. This plan might solve the technical problems caused by the unpredictable make-up of sludge and the efficiency of the processes used to remove and change lipids. The following factors can affect these efficiencies:

- Extraction methods: Lipid extraction methods that are usually used, such as solvent extraction, may not work for industrial sludge because they are complicated [129]. Advanced techniques such as microwave-assisted, ultrasound-assisted, and supercritical fluid extraction work better, but cost more and require special tools.
- Optimization of extraction parameters: Many factors, such as the choice of liquid, length of time the extraction lasts, temperature, and pressure, can be optimized to improve lipid extraction. Obtaining the appropriate conditions for different types of sludge can be difficult and requires extensive research and testing.
- Transesterification efficiency: Optimizing transesterification efficiency is very important when extracting lipids into biodiesel. Different types of catalysts, reaction times, temperatures, and amounts of free fatty acids (FFAs) and water in the material all have a significant impact on the transesterification process. The quantity and quality of biodiesel can be decreased by impurities that stop the catalysts from working and FFAs that cause soap to be made.
- Process integration: Integration of extraction and conversion processes must be performed efficiently to reduce energy use and operating costs. There may be significant benefits to reactive distillation and other continuous processes; however, they require complex control systems and careful process design.

Addressing these technical challenges is crucial for making biodiesel production from industrial waste a viable and sustainable alternative, facilitating broader adoption and implementation.

Integrating biodiesel production with other renewable energy systems can enhance sustainability and reduce the overall environmental footprint of the process. For example, coupling biodiesel facilities with solar or wind power systems can provide a renewable energy source for operational needs, thus minimizing reliance on fossil fuels. Additionally, biodiesel production can be integrated with biogas systems, in which by-products or residuals from one process are utilized as inputs for the other, creating a circular energy economy. This approach not only optimizes resource efficiency, but also aligns with the goals of a sustainable closed-loop energy system.

5.2. Improving Combustion Efficiency of Biodiesel from Industrial Waste

After discussing the conversion challenges, it is essential to consider the combustion efficiency of biodiesel derived from industrial wastes. Research has shown that advanced combustion techniques can significantly enhance the performance of biodiesel engines. For example, Charitha et al. [130] explored methods like Reactivity Controlled Compression Ignition (RCCI) and dual-fuel combustion, which improve efficiency and reduce emissions in biodiesel engines. Furthermore, emerging thermochemical conversion technologies have demonstrated potential for green energy production from sludge. For example, Viswanathan et al. [128] analyzed the gasification of sewage sludge into syngas using a downdraft gasifier. Their study revealed that optimizing parameters such as gasification temperature, fuel flow rates, and gasifying agent flow improves syngas quality, offering a pathway for cleaner energy solutions. By integrating advanced combustion and conversion technologies, biodiesel derived from industrial sludge can achieve a higher efficiency, making it a more attractive and eco-friendly alternative to traditional fuels.

5.3. Environmental and Health Concerns

The synthesis of biodiesel from industrial sludge presents favorable prospects for waste valorization and the creation of sustainable energy. However, it also results in notable environmental and health risks. These concerns are mainly related to the management and disposal of the leftover sludge and the possible release of pollutants.

After the extraction of lipids and manufacturing of biodiesel, a significant amount of leftover sludge remains, which presents the following difficulties in its management:

- Volume reduction: Although some organic material is removed during the extraction process, the remaining sludge volume is still significant. Implementing efficient techniques, such as dewatering and drying, is essential for minimizing waste disposal problems and lowering associated expenses.
- Residual composition: Leftover sludge generally consists of non-lipid organic materials, inorganic chemicals, and a range of possible pollutants. This must be carefully controlled to prevent environmental contamination. Disposal procedures must comply with rigorous regulatory criteria to prevent the contamination of soil and water [131].
- Alternative uses: Exploring alternate uses for leftover sludge can result in advantages for both the environment and the economy. Examples of waste management techniques that can reduce the need for landfill disposal and support a circular economy include composting, anaerobic digestion for biogas production, and the integration of sludge into construction materials.

The presence of diverse pollutants in industrial sludge presents environmental and health hazards if not appropriately handled throughout and following the biodiesel production procedure. These pollutants are as follows:

- Heavy metals: Industrial sludges, such as those generated by metal processing or petrochemical factories, may potentially include toxic heavy metals, such as lead, cadmium, and mercury [132]. The remaining sludge has the potential to accumulate these metals, and if not handled properly, it may be released into the environment through leaching, resulting in contamination of soil and bodies of water.
- Persistent Organic Pollutants (POPs): Industrial sludge can contain long-lasting organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated

biphenyls (PCBs). These harmful substances can accumulate in the food chain, resulting in significant health hazards for both humans and wildlife.

- Pathogenic microorganisms: Sargassum sludge from food and waste sectors can contain harmful bacteria. There may be fewer pathogens after pre-treatment and extraction, but it is still important to check any leftover sludge for dangerous bacteria before handling or discarding it.
- Volatile Organic Compounds (VOCs): Vaporized organic compounds (VOCs) can be released when sludge is handled. These VOCs could be detrimental for workers and worsen air pollution [133]. Limiting these risks requires effective control measures, such as ensuring sufficient airflow and using the right safety gear.

To enhance the feasibility and sustainability of biodiesel production from industrial sludge, it is crucial to address the associated environmental and health issues. Helping with trash management and working with the goals of renewable energy address these issues.

5.4. Regulatory and Policy Issues

To make biodiesel from industrial sludge, we need new scientific discoveries, the ability to make it economically viable, and the ability to easily navigate the rules and regulations set by the government. This section provides information about how incentives and subsidies affect waste-to-energy projects and how important it is to follow environmental rules.

Making biofuel from industrial sludge must follow strict environmental rules to be performed in a way that is good for the environment and will last. Some important aspects are as follows:

- Classification and disposal: If you want to remove or treat industrial sludge, you have to follow strict rules because it is considered hazardous. For the safe handling, treatment, and removal of sludge, these guidelines must be followed. This lowers risks to the environment and public health. To do this, rules must be followed to properly remove any leftover sludge, and possible pollutants must always be checked for.
- Emission control: For example, greenhouse gases (GHGs) and volatile organic compounds (VOCs) can be produced when industrial sludge is processed. For environmental agencies to minimize air pollution, facilities must follow the rules set by these agencies regarding emissions. Adopting the best methods and the most up-to-date tools for controlling emissions is essential to meet these strict standards.
- Wastewater treatment: Biodiesel production creates wastewater that needs to be treated to meet release regulations [134]. Adherence to water quality laws guarantees that the released water does not pollute nearby water sources, thereby safeguarding aquatic ecosystems and public well-being.
- Worker safety: Regulations require the implementation of safe working conditions to safeguard workers from the potential harm caused by the handling and processing of hazardous compounds in sludge. This entails furnishing suitable personal protective equipment (PPE), thorough training, and stringent safety regulations.

Governments and policymakers can provide various incentives and subsidies to encourage the adoption of biodiesel from industrial sludge [135,136]. The provision of financial subsidies can effectively mitigate economic obstacles and foster investment in waste-to-energy initiatives:

- Subsidies and grants: Financial assistance in the form of subsidies and grants can decrease the initial capital expenditure required to build biodiesel production facilities. This money can be used for research and development, implementing pilot initiatives, and expanding operations [137–140].
- Tax incentives: As a result of tax benefits and deductions, renewable energy projects may be a better financial choice for producing biodiesel from sludge. Incentives include lower company tax rates, faster equipment depreciation, and exemptions from certain environmental fees.

- Feed-in tariffs and renewable energy certificates: Feed-in tariffs, which set a fixed price for biodiesel produced from sludge, can be enforced by the government. This provides makers with a steady way to make money. For every unit of biodiesel, renewable energy certificates (RECs) can be obtained. These can then be traded with groups that must satisfy renewable energy goals [141].
- Funding for Research and Development: Through the funding of research and development, new ideas can be developed, leading to the creation of easier and cheaper ways to convert sludge into biodiesel. Forming partnerships with university institutions and working together with both public and private organizations can help people learn more and improve their technology.

Using government rewards and focusing on following the rules can make the creation of biodiesel from industrial sludge more appealing and possible, which will help achieve sustainable energy goals and protect the environment.

6. Thoughts on the Future and Study Directions

6.1. Enhancing Feedstock Quality

Industry wants to use industrial sludge to make production processes more efficient; therefore, future research and development in the biodiesel sector should focus on improving the feedstock. This section looks at the following two strategies that might work: changing the genes of bacteria that make sludge and making changes to how sludge is handled and managed [142].

6.1.1. Genetic Engineering of Sludge-Producing Microorganisms

Genetic engineering has significant potential to improve the lipid content and quality of microorganisms employed in sludge production. Scientists can improve the ability of these bacteria to produce lipids by changing their genes. This makes the process of making biodiesel more efficient and produces more fuel [143]. The following provides further information about the benefits of genetic engineering:

- Increased lipid biosynthesis: Genes involved in the production of lipids can be generated by changing their DNA. Microorganisms that collect more lipids may grow faster using this method, which makes sludge better for biodiesel production.
- Environmental resilience: Changing microorganism genes so they can handle external stressors such as changes in temperature and pH, and the presence of pollutants can make the production of lipids more reliable and consistent [143]. This ability to deal with and rebound from problems could lower the changes in the make-up of sludge, making the raw material more reliable.
- Selective lipid production: Researchers can increase the amount of good fats, such as triglycerides, while decreasing the production of bad substances by altering certain metabolic pathways. Using this approach, the overall quality of the raw materials can be increased, which can lead to the production of high-quality biodiesel.
- Sustainable carbon utilization: It is possible to create genetically modified bacteria to grow and produce lipids using carbon sources, such as waste biomass and carbon dioxide, that can be used repeatedly. This can also reduce the damage caused by biofuels from sludge to the environment.

6.1.2. Improved Sludge Management Practices

The use of effective sludge cleaning methods is important for obtaining the best-quality feedstock for biodiesel production [13,144,145]. Optimizing methods and using cutting-edge technologies to manage sludge can lead to a more consistent and improved product.

- Segregation and pretreatment: The quality of the material can be improved by separating the different types of industrial sludge based on where they come from and what parts they contain. Methods such as dewatering, mechanical separation, and chemical preparation before treatment can help concentrate the lipid-rich part and eliminate impurities, which improves the overall quality of the feedstock.

- Nutrient optimization: Changing the nutrients in the growing medium for microorganisms that make sludge can facilitate fat storage. Improving the supply of nutrients, such as nitrogen, phosphorus, and trace elements, can help microbes produce more lipids [16].
- Real-time monitoring and control: Real-time monitoring and control tools can help maintain conditions perfect for making lipids. Real-time data-driven changes to process factors, made possible by advanced sensors and automation technology, can ensure consistent feedstock quality.
- Minimizing non-lipid components: The quality of the fuel can be improved by making the process run smoother so that less non-lipid material is made in the sludge. Strategies such as using fewer harmful chemicals in factories and adopting more eco-friendly ways to make things can create sludge with higher amounts of lipids that are easier to treat to produce biodiesel.

6.2. Optimization of Production Processes

To get the most biofuel from industrial sludge, improve quality, and make the process last as long as possible, it is important to find the best ways to do things [146–148]. This section looks at the following two main ways to improve processes: making triggers work better and combining different stages of production.

6.2.1. Development of More Efficient Catalysts

Transesterification occurs quickly with the help of a catalyst. This process converts lipids from the industrial sludge into biodiesel [149,150]. Increasing the specificity and efficiency of catalysts can improve the overall production process.

- Heterogeneous catalysts: The main focus of this study is to develop heterogeneous catalysts that are better than regular homogeneous catalysts in a number of ways. Some of the benefits are that it is easier to separate from the reaction mixture, more stable, and can be used again. New materials such as metal oxides, zeolites, and supported metals have been studied to determine how well they work as catalysts in transesterification reactions [151].
- Enzyme-catalyzed transesterification: Enzyme-catalyzed transesterification is a very promising alternative to chemical catalysts. Enzymes can target certain chemicals precisely. Additionally, they work under mild reaction conditions and can handle contaminants, which makes it easier to produce biodiesel with higher output and better quality. Researchers have used protein engineering and immobilization techniques to make enzymes more stable, efficient, and cost-effective.
- Nanostructured catalysts: Nanostructured catalysts are unique because they have a large surface area, are more reactive, and are more efficient. Nanomaterials, such as nanoparticles, nanotubes, and nanocomposites, are being investigated to determine their potential for use in biodiesel production. By changing the nanostructure size, form, and content, researchers can fine-tune catalytic properties and reaction rates.

6.2.2. Integration of Production Steps

By merging and optimizing manufacturing stages, energy use and waste can be reduced and the general efficiency of the process can be increased [152]. Integration can be performed in the following ways:

- Sequential integration: By performing the extraction, pre-treatment, and transesterification steps in a single reactor or process line, less secondary processing is needed, and less material needs to be moved. This plan makes the process more efficient and reduces the operational costs. Sequential integration has been shown to streamline production flows, minimize interruptions, and enhance overall productivity by eliminating unnecessary transfer steps [153].

- Continuous-flow systems: Continuous-flow systems are good for increasing the output, scalability, and energy efficiency. When materials are processed continuously with these systems, productivity increases, and product quality improves. Continuous-flow systems facilitate uninterrupted processing, which not only increases scalability but also ensures consistent product quality, making them ideal for large-scale biodiesel production [153].
- Simultaneous integration: Using synergistic effects to improve overall performance is the means of simultaneous integration. Extracting and transesterifying can happen at the same time using reactive distillation, membrane separation, and solid-phase extraction. As a result, there will be shorter response times and higher product yields. Through methods such as reactive distillation, simultaneous integration maximizes the use of resources by reducing the reaction times, leading to higher yields and efficient processing [153].
- Modular design: Biodiesel production systems can be changed and added because they use a modular design. The separate parts for pre-treatment, lipid extraction, and transesterification can be connected or changed in different ways depending on the feedstock, the production capacity that is needed, and the need for process optimization. Using a modular design makes it easy to add to and change existing buildings, thereby reducing capital costs and downtime. The flexibility of modular design allows biodiesel production systems to be tailored and expanded as needed, adapting to different types of feedstock and optimizing production capacity efficiently [153].

6.3. Sustainability and Scalability

Sustainable and scalable biodiesel production from industrial sludge as a green energy source is important for its long-term viability [59,154]. This section looks at the following two important topics: the life cycle review of biodiesel made from sludge, and whether it is possible to make more on an industrial scale.

6.3.1. How Biofuel from Sludge Affects the Environment over Its Whole Life

A full life cycle assessment (LCA) is required to determine how the production of biodiesel from industrial sludge affects the environment and how long it will last. The idea of LCA includes the entire process of making biodiesel, from getting the feedstock, preparing it for use, and throwing it away at the end. With this method, environmental sites and areas that can be used for improvement can be found. These issues are described as follows:

- Environmental impact quantification: The LCA checks the environmental effects of biodiesel production, including greenhouse gas emissions, energy use, water use, land use, and effects on ecosystems. Scientists can determine whether biodiesel made from garbage is better for the environment by examining how it differs from fossil fuels and other biofuels.
- Resource efficiency and environmental burden: Utilizing an LCA helps find possible ways to improve resource efficiency and lower environmental effects throughout the entire production process. Energy and water efficiency, trash reduction, and the use of environmentally friendly methods to obtain feedstock are all important areas that can be improved.
- Sensitivity analysis: Researchers can determine how uncertainty and variation in important factors affect the general sustainability of biodiesel production using sensitivity analysis within the LCA framework. This study provides useful information that helps us make choices and decide which research and development topics are the most important for making the world more sustainable.
- Comparative studies: The LCA-based comparative studies can show how environmentally friendly biodiesel made from sludge compares to other types of sustainable and non-renewable energy sources. These studies provide lawmakers and businesses

with a full picture of the pros and cons, which helps them move forward with more environmentally friendly energy options.

The LCA has been helpful in understanding the environmental costs and benefits of biofuel production. This is particularly true when using advanced extraction methods such as supercritical CO_2, which has been shown to be better for the environment in similar cases [155]. The LCA studies that have been performed on biofuel production are shown in Table 4. Many different locations were examined in these studies, and different LCA methods were used to determine how making biodiesel from different raw materials affects the climate. As reported by Angili et al. [156], the IMPACT 2002 method was used in Poland. This process is based on the catalytic intermediate pyrolysis of rapeseed meal. This study provides useful information regarding how this process affects the world. The ISO 14040 [157] method was used to test the production of biodiesel from second-generation feedstocks, such as Castor, Croton, and Jatropha. This study shows that these alternative raw materials have significant potential [158]. Germany used the ReCiPe 2016 midpoint method to check how well the process of obtaining lipids from wastewater treatment sludge (WWTS) was working. This research has provided information on how trash can be used to make biodiesel [159]. Through the IMPACT world+ method, researchers in Canada have examined how biodiesel can be made from fish waste for green microgrids, focusing on the importance of biodiesel in renewable energy systems [117]. The Eco-indicator 99 method, which is used in Malaysia, checks the amount of biodiesel produced using magnetic biochar mixed with oil from used palm kernel shells. The use of waste materials in creative ways to produce biodiesel is demonstrated by this process [160]. In Spain, the ReCiPe 2016 method is mostly concerned with making biofuel production from used cooking oil more efficient. The goal is to be more eco-friendly [161]. The R programming language was used to compare the LCA of biodiesel production from palm oil and the large-scale solar energy output in Malaysia. This study presents the number of renewable energy sources that can be used [160]. The R programming language has made it possible to perform a social LCA of biodiesel feedstock in Brazil. This provides a more complete picture of the social effects of making biodiesel [162]. These studies stress the importance of LCA in understanding how biodiesel production affects the environment, economy, and society. The different techniques and materials examined in these studies show the complexity and changing biodiesel production. To make biodiesel production sustainable and effective, specific strategies are required.

Table 4. Concise summary of LCA studies on biofuel production.

Method	Location	Indicators	References
IMPACT 2002	Poland	Comparative LCA of Catalytic Intermediate Pyrolysis of Rapeseed Meal	[156]
ISO 14040	Uganda	LCA of biodiesel from second-generation feedstocks (Castor, Croton, Jatropha)	[157]
ReCiPe 2016 Midpoint	Italy	LCA of lipid extraction and transformation from Waste Water Treatment Sludge (WWTS)	[159]
IMPACT world+	Canada	LCA of biodiesel production from fish waste for green microgrids	[117]
ReCiPe 2016 Midpoint	Malaysia	LCA of biodiesel production from black soldier fly larvae on pre-treated sewage sludge	[160]
–	UK	LCA of biodiesel production from rapeseed oil, considering process parameters	[161]
Eco-indicator 99	Malaysia	LCA of biodiesel production using impregnated magnetic biochar from waste palm kernel shell	[163]
ReCiPe 2016	Spain	LCA optimization for eco-efficient biodiesel production using waste cooking oil	[164]

Table 4. *Cont.*

Method	Location	Indicators	References
R language	Malaysia	Comparative LCA of large-scale solar vs. biodiesel production from palm oil	[165]
R language	Brazil	Social LCA of biodiesel feedstocks in Brazil	[162]
ISO 14040 and ISO 14044	Malaysia	LCA of palm biodiesel upstream production in Malaysia	[166,167]
Open LCA v1.10.3	India	LCA of biodiesel from estuarine microalgae	[168]
ISO 14044	Mexico	Environmental assessment of animal fat-based biodiesel	[169]

6.3.2. Potential for Industrial Scale-Up

The ability to easily increase the amount of biodiesel produced from industrial sludge is important for its widespread use and economic success. The following factors can affect the likelihood of economic growth:

- Feedstock availability and consistency: For industrial-scale production, it is important to test the ease and regularity of the industrial sludge feedstock. Understanding how the composition of sludge changes over time, how quickly it is made, and where it can be found in different areas is important for building strong production and supply lines.
- Technology maturity: Biodiesel production from sludge is ready for large-scale use in industry depending on the extent of the methods for extraction, pre-treatment, and transesterification. Ensuring that the processes are always more reliable, cost-effective, and efficient is necessary for large-scale production.
- Economic feasibility: It is very important to determine whether making biodiesel from sludge on a large scale is affordable. Getting feedstock at low cost, streamlining production methods, good market conditions, and government incentives are all important for ensuring that large-scale production is economically viable.
- Regulatory and policy support: Regulatory systems and policy incentives can help or hurt the widespread use of biodiesel production from sludge. The creation of clear rules, helpful policies, and appealing rewards for the production of renewable energy and reuse of waste can help create an atmosphere that encourages investment and growth. Policymakers must actively participate in creating helpful rules and incentives to allow production to grow on a larger scale.
- Infrastructure and logistics: Establishing the infrastructure and procedures needed to produce a large amount of biodiesel is very important. This includes building places to gather, process, and distribute feedstock as well as making the best use of transportation networks. Building the necessary infrastructure can be made easier when government agencies and people in business work together.

6.4. Policy and Economic Framework

There is a need for an economic and social environment that allows biodiesel to be made from industrial sludge. The next section looks at how government policies have impacted the growth of programs that turn trash into energy and the creation of business models for long-term production.

6.4.1. Government Policies and Incentives

Policies made by the government help make more biofuel from industrial sludge by making it easier to follow the rules, giving money to people who do so, and improving infrastructure. These factors are as follows:

- Regulatory frameworks: Establishing clear and helpful rules is important to help biodiesel production facilities start and run smoothly. To ensure that the process of making biodiesel from sludge follows all legal and environmental rules, the rules should include aspects of garbage management, protection of the environment, and use of renewable energy.

- Financial incentives: Governments can offer various cash incentives to encourage people to invest in waste-to-energy projects. Supports such as subsidies, grants, tax credits, and low-interest loans are meant to make conditions financially easier for producers and speed up the adoption of biodiesel production methods [170]. These benefits make investing in biodiesel production more appealing and financially viable.
- Research and development funding: Issuing funds for research and development (R&D) projects is necessary to advance the technologies and methods used to create biodiesel from sludge. Federal support for research and development (R&D) can lead to new ideas, higher productivity, and lower costs, which make biodiesel production more competitive and long-lasting.
- Infrastructure development: Building necessary systems for collecting, transporting, and processing waste is important for biodiesel output to grow [12,171]. Governments can invest money in building projects that make it easier to handle and process industrial sludge. This ensures a steady supply of raw materials for biodiesel production.

6.4.2. Economic Plans for Long-Term Production

It is very important to use economic models to estimate whether and for how long it will be possible to convert industrial waste into biodiesel. Knowing how costs change over time, how big the market might be, and whether the production process can make money are all items that the following models can help with:

- Cost-benefit analysis: A full cost–benefit study can be performed to determine whether making biodiesel from sludge is a good idea [148,172,173]. In this study, the cost of fuel, cost of production, initial investment, and amount of money that could be made from selling biodiesel were considered. Environmental and social effects were also examined. For example, getting rid of trash costs less and produces less greenhouse gas.
- Market dynamics: Understanding how the biofuel market works is necessary to ensure that the output will continue in the future. Markets for biodiesel need to have supply and demand trends, prices that work, and different types of companies competing in them studied using economic models. By examining the possible market challenges and possibilities, producers can make smart decisions and create effective market strategies.
- Sustainable business models: Economic, environmental, and social issues must be considered when creating business models that will last. Consequently, resources are used more efficiently, waste is reduced, and everyone benefits. Some examples include models of the circular economy, in which garbage is constantly recycled and reused, and community-based models that involve people in the area making and distributing biodiesel. Figure 6 shows how the circular economy is used to produce biofuels from industrial sludge. The diagram shows how recycling and reusing garbage materials work together to make things better for everyone in the community and business. This picture fits with the sustainable business models we discussed, where minimizing waste and making the best use of resources are key to making the economy last.
- Public–private partnerships (PPPs): When the public and private sectors work together, biofuel production becomes more economically stable. Partnerships between the public and private sectors use the strengths and resources of both sectors. They make it possible for people to share technology, spend money, and develop new ideas.

Governments can offer regulatory assistance and financial incentives, whereas private companies contribute to expertise, capital, and operational efficiency.

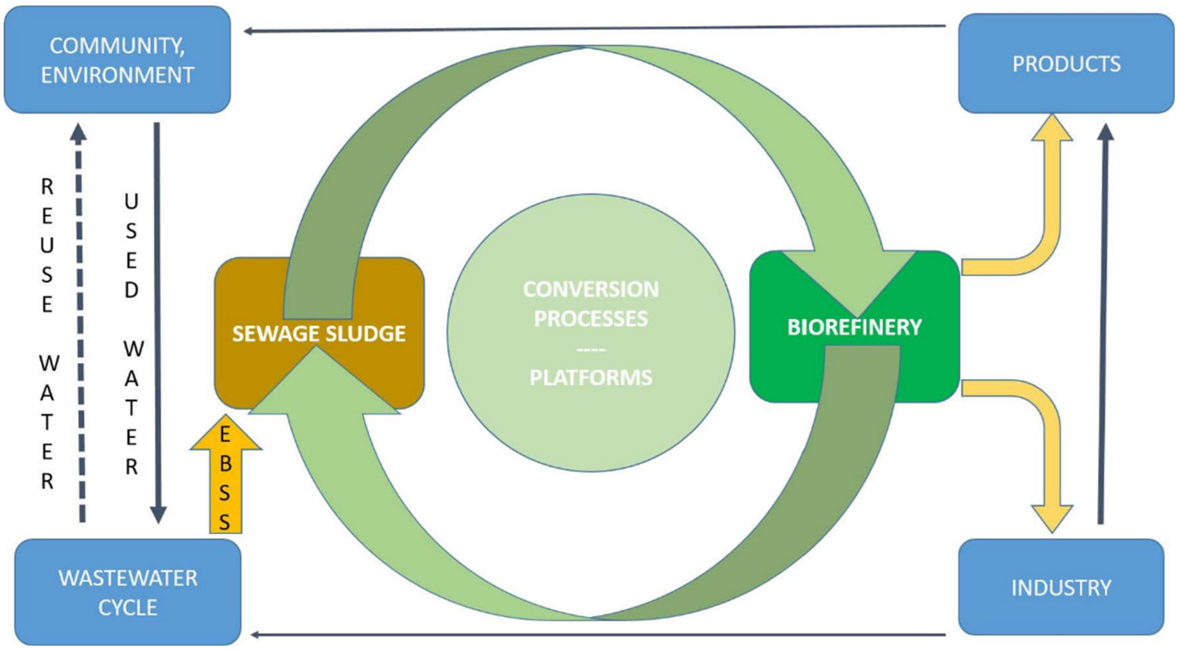

Figure 6. Conceptual progression of sewage sludge through conversion processes within a circular economy [174].

7. Conclusions

This study investigated the potential of industrial sludge as a viable raw material for biodiesel production, with the aim of addressing environmental challenges while contributing to sustainable energy solutions. Through detailed analysis, key factors influencing biodiesel yield were identified, including sludge composition, pre-treatment techniques, and process optimization methods. The findings revealed that biodiesel derived from industrial sludge exhibits properties comparable to those of conventional biodiesel, demonstrating its suitability for blending and energy applications. However, challenges such as cost-effectiveness, scalability, and regulatory compliance must be addressed to ensure feasibility on a commercial scale. The novelty of this research lies in its focus on utilizing waste biomass, specifically industrial sludge, as feedstock for biodiesel production, a niche area that combines waste management with renewable energy generation. Optimizing the production process and assessing economic viability contribute to a broader field of biofuel technology and circular economy approaches. Notably, integrating biodiesel production with other renewable energy systems could enhance energy efficiency and resource utilization, which is recommended for future investigations. Future studies should focus on overcoming scalability challenges, improving process efficiency, and exploring policies that support industrial-scale applications. Further research is required to conduct a comprehensive environmental impact assessment to quantify the sustainability benefits of industrial sludge-based biodiesel. This study contributes to the current understanding of biodiesel production from waste materials and provides a foundation for future advancements in sustainable fuel technology.

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