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REVIEW ARTICLE

Optimizing biodiesel production from waste with computational chemistry, machine learning and policy insights: a review

Ahmed I. Osman[1,2] · **Mahmoud Nasr**[2] · **Mohamed Farghali**[3,4] · **Ahmed K. Rashwan**[5] · **Adel Abdelkader**[2] · **Ala'a H. Al-Muhtaseb**[6] · **Ikko Ihara**[3] · **David W. Rooney**[1]

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Abstract

The excessive reliance on fossil fuels has resulted in an energy crisis, environmental pollution, and health problems, calling for alternative fuels such as biodiesel. Here, we review computational chemistry and machine learning for optimizing biodiesel production from waste. This article presents computational and machine learning techniques, biodiesel characteristics, transesterification, waste materials, and policies encouraging biodiesel production from waste. Computational techniques are applied to catalyst design and deactivation, reaction and reactor optimization, stability assessment, waste feedstock analysis, process scale-up, reaction mechanims, and molecular dynamics simulation. Waste feedstock comprise cooking oil, animal fat, vegetable oil, algae, fish waste, municipal solid waste and sewage sludge. Waste cooking oil represents about 10% of global biodiesel production, and restaurants alone produce over 1,000,000 m^3 of waste vegetable oil annual. Microalgae produces 250 times more oil per acre than soybeans and 7–31 times more oil than palm oil. Transesterification of food waste lipids can produce biodiesel with a 100% yield. Sewage sludge represents a significant biomass waste that can contribute to renewable energy production.

Keywords Computational chemistry · Machine learning · Energy crisis · Waste-based biodiesel · Renewable energy · Sustainability

Introduction

In recent decades, extensive reliance on oil-based products has led to a profound energy crisis, widespread environmental pollution, and a surge in health problems, including heart disease and cancer. Fossil fuels like natural gas, oil, and coal have dominated the global energy landscape, constituting over 80% of the world's energy production, primarily driven by carbon emissions from these sources (Alalaiwat and Khan 2023; Esmaeili 2022). Despite technological improvements and energy efficiency laws, the increase in global population and economic growth has led to a rise in energy consumption, which has not been offset by the gains made in energy efficiency. Additionally, the ongoing conflict between Russia and Ukraine has triggered an energy crisis, significantly impacting households' energy costs for heating, cooling, and transportation. In 2021, the European Union relied on imports for over 45% of its gas supply, representing nearly 40% of its total gas consumption (Farghali et al. 2023b). The extensive use of non-renewable energy sources and increasing industrialization have resulted in the release of

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Ahmed I. Osman and Mahmoud Nasr have contributed equally to this review.

✉ Ahmed I. Osman
aosmanahmed01@qub.ac.uk

✉ Mahmoud Nasr
mahmoud.nasr62@sci.svu.edu.eg

[1] School of Chemistry and Chemical Engineering, Queen's University Belfast, David Keir Building, Stranmillis Road, Belfast, Northern Ireland BT9 5AG, UK

[2] Nanocomposite Catalysts Lab., Chemistry Department, Faculty of Science at Qena, South Valley University, Qena 83523, Egypt

[3] Department of Agricultural Engineering and Socio-Economics, Kobe University, Kobe 657-8501, Japan

[4] Department of Animal and Poultry Hygiene and Environmental Sanitation, Faculty of Veterinary Medicine, Assiut University, Assiut 71526, Egypt

[5] Department of Food and Dairy Sciences, Faculty of Agriculture, South Valley University, Qena 83523, Egypt

[6] Department of Petroleum and Chemical Engineering, College of Engineering, Sultan Qaboos University, Muscat, Oman

large amounts of greenhouse gases, leading to environmental degradation and a rise in global temperatures (Wang et al. 2022a). The global average atmospheric carbon dioxide concentration has seen a significant increase, surging from 285 ppm in 1850 to 419 ppm in 2022 (Chen et al. 2022). According to estimations by the United Kingdom Meteorological Office, the global average surface temperatures have been projected to rise by approximately 0.97–1.21 °C between 1850 and 2022, with an average estimate of 1.09 °C. Additionally, the year 2022 is anticipated to be one of the warmest years on record (Sangomla 2022). Moreover, greenhouse gas emissions are predicted to increase by 50% by 2050, primarily due to carbon dioxide emissions from non-renewable energy sources (Chen et al. 2022; Draper et al. 2022; Mukhtar et al. 2022). As a result of ongoing increases in atmospheric carbon dioxide, global warming has brought the globe to the brink of an environmental disaster (Bahman et al. 2023; Halawy et al. 2022).

Energy is a fundamental necessity for our survival, and as the demand for energy sources surges, optimizing resource utilization becomes imperative (Farghali et al. 2023a). The limited availability of traditional energy sources, coupled with escalating global demand, underscores the importance of alternative fuels (Maheshwari et al. 2022). While renewable and green energy resources are in use, none can completely replace conventional fossil fuels (Brahma et al. 2022). Biofuels, particularly biodiesel, have garnered significant attention as a renewable, biodegradable, and non-toxic fuel with lower emissions compared to regular diesel (Arslan et al. 2022; Brahma et al. 2022; Yaashikaa et al. 2022). Biodiesel boasts superior chemical and physical properties when compared to petrol-diesel (Osman et al. 2023a). The direct use of biodiesel or biodiesel blends leads to substantial reductions in combustion gases and carbon monoxide emissions (Sarwer et al. 2022). Indonesia and the United States are the world's largest biodiesel producers, generating 7.9 and 6.5 billion liters in 2019, respectively, and by 2025, the United States is expected to produce over 1 billion gallons of biodiesel. Estimates suggest that biodiesel could replace up to 7 volume% of the world's fossil fuels by 2030 (Babadi et al. 2022). It presents a feasible solution to the dual challenges of fossil fuel depletion and environmental degradation (Borah et al. 2019). However, alternative fuels face significant challenges, including special handling requirements, high costs, low energy density compared to petroleum-based fuels, and inadequate supply to meet nationwide requirements (Maheshwari et al. 2022).

The production of biodiesel can utilize waste materials such as waste cooking oils, animal fats, various non-edible vegetable oils, and municipal waste as raw materials (Du et al. 2016). Waste-based biodiesel has its origins in World War II and the energy crises of the 1970s when alternative oil resources were sought due to fuel shortages. In the 1980s, the trans-esterification method enabled biodiesel production from waste materials (Ayadi et al. 2016). Therefore, waste-based biodiesel is regarded as the second generation of biodiesel production (Heidari and Wood 2021). The benefits of converting waste to biodiesel are multifaceted, encompassing waste management, reduced greenhouse emissions, economic stability, energy resource diversification, and climate change mitigation (van Eijck et al. 2014). However, the high viscosity of biodiesel compared to petroleum-based fuel posed challenges.

Thus, optimizing waste-based biodiesel production represents a critical step towards sustainable energy solutions. Computational chemistry and machine learning techniques have emerged as invaluable tools in this endeavor. Computational chemistry aids in deciphering the complex chemical reactions involved in biodiesel production, offering insights into reaction mechanisms, kinetics, and catalyst design. Machine learning, on the other hand, empowers precise predictions and optimization of various biodiesel production parameters, enhancing process efficiency and yield. Together, these cutting-edge approaches enable a more comprehensive understanding of waste-based biodiesel production, facilitating the development of efficient and eco-friendly processes to meet the growing demand for renewable energy sources while reducing the environmental footprint (Abdelbasset et al. 2022; Ibrahim 2021). Figure 1 illustrates the utilization of various waste resources for biodiesel production, incorporating pretreatment and transesterification processes. These processes are further enhanced through the integration of machine learning and computational chemistry techniques.

This article review delves into the world of biodiesel production, exploring the potential of waste materials as sustainable feedstocks. With a specific focus on computational chemistry and machine learning techniques, it highlights innovative approaches to optimize the biodiesel production process. The discussion covers the various waste materials that can be used to produce biodiesel, their availability and suitability for the process, and the chemical reactions involved in the conversion process. Additionally, the review addresses policy recommendations for fostering the integration of waste-based biodiesel into existing energy systems, thereby promoting environmental sustainability and economic stability.

Computational chemistry in the production of biodiesel from waste

Computational chemistry is crucial in various fields, such as chemistry, biochemistry, chemical physics, and material science. It is a discipline that utilizes fundamental principles from physics to examine a wide range of molecular

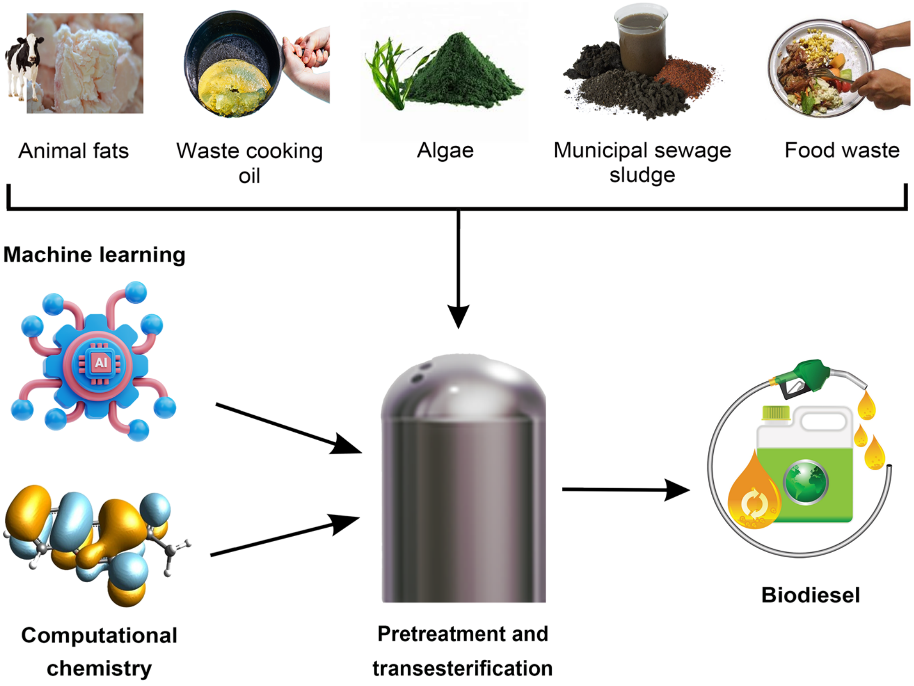

Fig. 1 Utilization of different waste resources for biodiesel production through pretreatment and transesterification processes enhanced by machine learning and computational chemistry. The figure illustrates the diverse range of waste resources utilized for biodiesel production, including animal fats, waste cooking oil, algae, municipal sewage sludge, and food waste. These waste materials undergo pretreatment processes to remove impurities and enhance their suitability for biodiesel production. Computational chemistry techniques play a significant role in understanding the complex chemical reactions involved in the pretreatment and transesterification processes. By leveraging computational chemistry, researchers can optimize reaction conditions, catalyst selection, and process parameters, leading to improved biodiesel yield and quality. Machine learning algorithms are employed to develop predictive models that aid in process optimization and parameter selection. The integration of machine learning and computational chemistry enables precise predictions and efficient utilization of waste resources for sustainable biodiesel production, contributing to waste management, renewable energy generation, and environmental sustainability

properties and phenomena. Advanced computational techniques enable researchers to investigate molecular structures, thermodynamics, spectroscopic data, reaction rates, and dynamics with exceptional precision and accuracy. Computational chemistry can simulate different phases, including gases, liquids, solids, solutions, and interfaces (Osman et al. 2023b). One of the key advantages of computational chemistry is its ability to simulate adsorption and desorption processes, considering factors such as surface composition, spatial configuration, solution environment, ionic strength, and solution pH. Additionally, it can calculate and interpret spectroscopic data from techniques such as infrared, ultraviolet, nuclear magnetic resonance, and X-ray spectroscopy. The chosen level of theory greatly influences the accuracy and efficiency of these calculations and simulations (Ahmed et al. 2023; Osman et al. 2023b).

Predictive trends may be found using computational approaches that effectively map important chemical features, such as various catalytic materials' carbon and oxygen binding energies. Model surfaces with realistic compositions and structures based on experimental characterizations must be used in computer investigations to yield the most insightful understanding of reaction processes. Now, density functional theory-based ab initio calculations are expensive and frequently limited by computer resources to somewhat idealized model systems. But even when used to interpret experimental kinetic data or create general catalyst design parameters, consistent computational results from realistic, well-built, simplified models may still offer insightful information (Murphy and Xu 2018).

Quantum solutions based on the fundamental axioms of quantum mechanics can help with sustainable energy research. By employing orbitals, their occupations, electron interactions, and excitations as crucial variables, correlated wavefunction theories provide maximum accuracy. Correlated wavefunction approaches, on the other hand, are computationally costly, restricting their use to tiny or medium-sized molecules. Local correlation techniques make use of electron correlation's nearsightedness to ignore or approximate spatially separated excitations. Quantum solutions, which are based on the theory that regulates electron behavior, play critical roles in tackling many challenges connected to sustainable energy research. Theoretical quantum solutions are based on fundamental physical principles and provide prediction assessments of molecule and material characteristics that are frequently completely independent of an experiment. Atomic-scale simulation, investigation of materials and systems at the atomic scale, and analysis of their electrical characteristics can cover knowledge gaps that experiments cannot address. However, using quantum mechanics should be done cautiously because sample characteristics can all impact the results (Dieterich and Carter 2017).

Computational chemistry plays a significant role in the production of biodiesel from waste. By employing advanced computational techniques, researchers can model and simulate the chemical reactions in the biodiesel production process, providing valuable insights and guidance for optimizing production efficiency. One of the key aspects where computational chemistry is crucial is in the design and development of catalysts. Catalysts are essential in the transesterification reaction, which converts waste oils and fats into biodiesel. Computational chemistry allows researchers to study and analyze the interactions between catalysts and reactants at the molecular level. This enables the identification and design of highly effective catalysts that can accelerate the reaction rate and improve the overall yield of biodiesel (Aghbashlo et al. 2021). Furthermore, computational chemistry can assist in optimizing reaction conditions such as temperature, pressure, and solvent composition (Dharmegowda et al. 2022). Through molecular simulations, researchers can investigate the impact of different parameters on the reaction kinetics and select the optimal conditions that maximize the conversion of waste oils into biodiesel. Another area where computational chemistry proves valuable is in understanding the properties of biodiesel molecules. Researchers can use computational methods to study the physicochemical properties of biodiesel, including its viscosity, density, and combustion characteristics. This knowledge is essential for assessing the performance and compatibility of biodiesel as a fuel and ensuring its efficient utilization in engines and vehicles. Moreover, computational chemistry can provide insights into biodiesel's stability and degradation mechanisms. By studying the molecular structures and analyzing reaction pathways, researchers can identify potential degradation pathways and develop strategies to enhance biodiesel products' stability and shelf life. Figure 2 illustrates the various methods of computational chemistry and their application in the production of biodiesel.

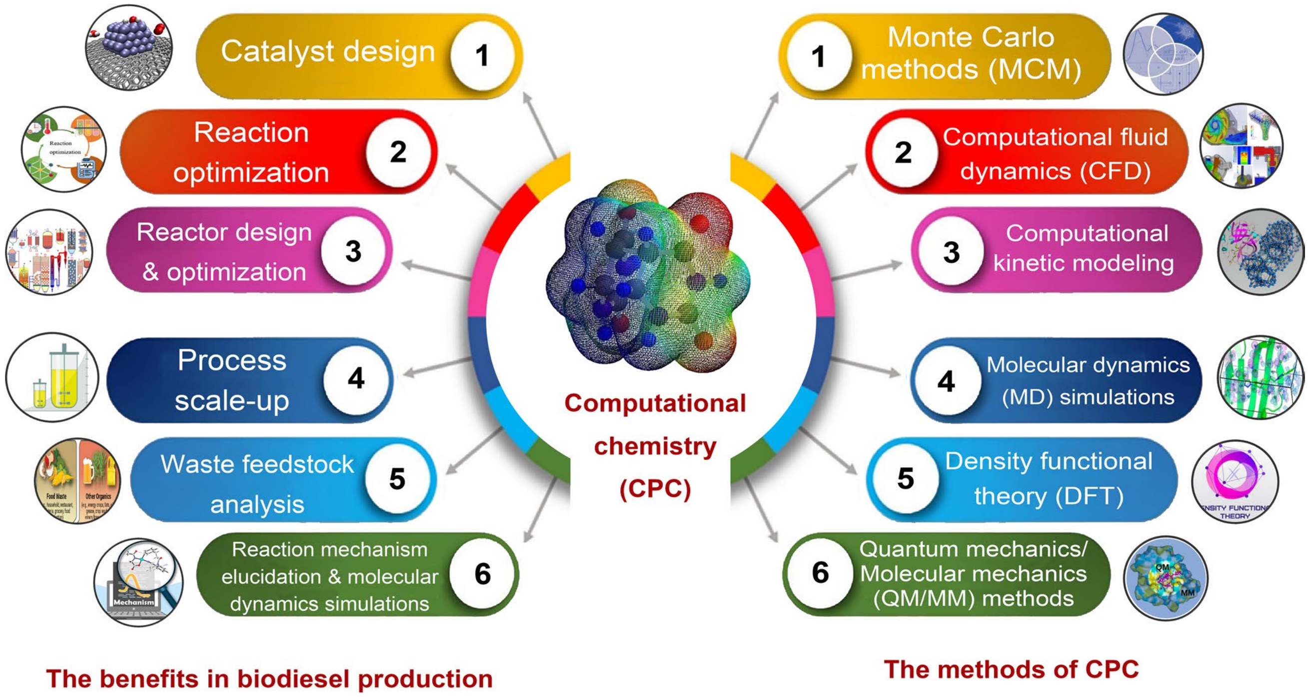

Fig. 2 Computational chemistry techniques and their application in biodiesel production. The figure depicts computational chemistry techniques vital for biodiesel production from waste. It covers catalyst design for tailored catalyst development, reaction optimization for improved yields, and reactor design to enhance production conditions. Waste feedstock analysis selects suitable materials, process scale-up transitions to commercial scale, reaction mechanism elucidation dissects pathways, and molecular dynamics simulations aid in catalyst design and reaction understanding. These computational tools revolutionize biodiesel production, offering insights and optimizations to develop sustainable and efficient processes from various waste sources

Computational techniques used for biodiesel production from waste

Computational chemistry plays a significant role in biodiesel production by providing insights into reaction mechanisms, catalyst design, and optimization. Here are some examples of computational chemistry models and techniques employed in biodiesel production:

Molecular dynamics simulations (MD): Many scientific areas, including chemical physics, materials science, and biophysics, have benefited greatly from molecular dynamics simulations. This computational methodology has proven extremely useful in the detailed characterization of biomolecular systems, including complementarity with experimental data, experimental design optimization, and prediction of relevant properties for chemical systems that are expensive or difficult to handle experimentally (Filipe and Loura 2022). Molecular dynamics simulations are used to study the behavior and interactions of molecules in biodiesel production (Hwang et al. 2014). They provide insights into the structure, dynamics, and properties of biodiesel molecules, catalysts, and other components. Molecular dynamics simulations can help in understanding reaction mechanisms (Ibrahim 2021), optimize catalysts, and analyze biodiesel's stability and properties (Bravo-Suárez et al. 2013). However, there is little research on the crucial characteristics of fatty acids, which are biodiesel precursors. Experimenting to determine key qualities for fatty acids is difficult owing to their ability to self-associate due to the presence of carboxylic groups via hydrogen bonds. These parameters can be determined using molecular simulation approaches (González et al. 2022). The thermal behavior of biodiesel (Yan et al. 2023), kinematic viscosity, and fuel density are investigated using molecular dynamics simulations (Yang et al. 2023a).

Density functional theory (DFT): Density functional theory is a quantum mechanical method used to calculate molecules' electronic structure and properties. It can be applied to study the energetics and reactivity of biodiesel production reactions, as well as the properties of catalysts and reactants. Density functional theory calculations provide valuable information about reaction pathways, energetics, and activation barriers (Ju et al. 2019; Moses et al. 2007; Ning et al. 2020; Osman et al. 2023b). Although experimental studies can help us understand the reactions catalyzed by heterogeneous acids, some more detailed mechanisms, such as elementary reactions and reaction paths, must still be defined using molecular simulation based on density functional theory (Ning et al. 2020). The acid-catalyzed transesterification mechanism for biodiesel production from waste cooking oils can be investigated using the density functional theory model (Li et al. 2018).

The density functional theory module was used by Li et al. (2018) to analyze the acid (H^+)-catalyzed transesterification process of methanol and oleic acid monoacylglycerol. Path 1, Path 2, and Path 3 were created to represent the one-step transesterification without a catalyst and possible pathways of substitution nucleophilic bimolecular (SN2) and substitution nucleophilic unimolecular (SN1) reaction processes with H^+-based catalysts. According to the computed structural, thermodynamic, and kinetic data, H^+-based catalysts could efficiently minimize the activation energy for the transesterification reaction, and Path 2, based on the substitution nucleophilic bimolecular reaction mechanism, was the best reaction path. The molecular simulation based on density functional theory can deeply reveal its catalytic reaction mechanism (Li et al. 2022). Ning et al. (2020) synthesized various heterogeneous acid catalysts by incorporating phosphotungstic acid onto bamboo-activated carbon and utilized them for catalyzing esterification in biodiesel production. The catalyst demonstrated excellent performance in catalyzing the esterification of oleic acid, achieving a maximum efficiency of 96%. The catalyst also exhibited satisfactory renewability, with a regenerated catalyst achieving an efficiency of 93%. The density functional theory results provided insights into the esterification process, revealing an activation barrier of 19.73 kcal/mol and a reaction energy of 15.83 kcal/mol. This study highlights the promising catalytic capabilities of phosphotungstic acid supported on bamboo-activated carbon for esterification in biodiesel production. The findings from density functional theory analysis provide valuable information regarding the activation barrier and reaction energy involved in the esterification process. Kim et al. (2022) used density functional theory calculations to examine the electronic and catalytic activity of the single sodium-doped graphitic carbon nitrides catalyst for efficient biodiesel production via triglyceride transesterification.

Quantum mechanics/molecular mechanics (QM/MM): QM/MM methods combine quantum mechanical calculations (often density functional theory) with molecular mechanics simulations. They are useful for studying complex systems where both the active site, like the catalyst and the surrounding environment, like the solvent, play significant roles (Quesne et al. 2019; Rungrotmongkol et al. 2007; Senn and Thiel 2009). QM/MM simulations can provide insights into reaction mechanisms, catalyst-substrate interactions, and the influence of the surrounding environment on the biodiesel production process. The molecular mechanism of sonication-induced improvement in the kinetics of lipase-catalyzed processes for biodiesel synthesis is thoroughly investigated (Kumar et al. 2023a). Novel insights are gained into the precise nature of interactions between substrates/products and lipase enzymes on a molecular level by determining the structure of binding pockets of lipases, visualizing binding pockets in various secondary structure motifs, and docking analysis of ligands with lipases using hybrid QM/MM concepts.

Kinetic modeling: Computational kinetic modeling involves developing mathematical models based on experimental data and theoretical calculations to describe the reaction kinetics of biodiesel production. These models can be used to predict reaction rates, optimize reaction conditions, and assess the impact of various parameters on the process efficiency (Hough et al. 2016; Jagaba et al. 2022; Manion and McGivern 2016; Norinaga and Deutschmann 2007). To produce biodiesel, waste cotton-seed cooking oil is microwave-assisted transesterified (Sharma et al. 2019a). The research focuses on optimizing the kinetic modeling of this process. A response surface approach based on a complete factorial design method was used to improve process parameters such as catalyst loading, reaction time, and methanol-to-oil ratio. Kostic et al. (2016) studied kinetic modeling and optimization of the esterification of the oil derived from wasted plum stones as a pretreatment step in biodiesel manufacturing. In addition, Gaurav et al. (2019) presented a kinetic model for converting model yellow grease, a mixture of waste cooking oil and animal fats, into biodiesel using a heteropolyacid catalyst supported on alumina (HSiW/Al_2O_3) in a batch autoclave. They prepared three model yellow grease feeds by incorporating palmitic, oleic, and linoleic acids into canola oil to simulate real-world conditions. The study developed a pseudo-homogeneous kinetic model that accounted for both esterification and transesterification reactions. By determining rate constants and activation parameters, the research validated the model's accuracy by comparing it with experimental biodiesel data obtained from commercial yellow grease feed processing. Notably, the calculated biodiesel production closely matched experimental results for feeds containing 12.26 wt.% palmitic and linoleic acid, whereas the feed with oleic acid exhibited a higher conversion rate due to its faster esterification kinetics. This kinetic model has the potential to be applied to various catalyst systems, offering valuable insights for process design and cost-effective production of sustainable biodiesel from non-food grade oils with high free fatty acids content.

Moreover, Hazrat et al. (2022) conducted a study on process optimization and reaction kinetics modeling for the two-stage esterification-transesterification reactions of waste cooking oil biodiesel. Optimal conditions were determined for both the esterification and transesterification processes. For the esterification process, the optimal conditions were as follows: a methanol-to-oil molar ratio of 8.12:1, 1.9 wt.% sulfuric acid content of the waste cooking oil, a reaction temperature of 60 °C, and a reaction time of 90 min. On the other hand, the optimal conditions for the transesterification process were found to be a methanol-to-esterified oil molar ratio of 6.1:1, 1.2 wt.% potassium hydroxide catalyst content of the esterified oil, a reaction temperature of 60 °C, and a reaction time of 110 min in a batch reactor system. After determining the optimized process parameters, the researchers developed reaction kinetic models for both the esterification and transesterification processes. Two types of kinetics modeling were employed. The overall process conversion efficiency was calculated to be 97.4%, based on the yield efficiency of both processes. The fatty acid composition of the produced biodiesel was analyzed, revealing the highest amount of methyl oleate at 44.1 wt.%, followed by methyl linoleate and methyl palmitate at 23.5 wt.% and 16.5 wt.%, respectively. Serrano et al. (2015) studied the kinetic modeling of biodiesel production from waste salmon oil, specifically salmon oil obtained from salmon silage in a tricanter centrifuge. The kinetic parameters were varied to obtain the most satisfactory data. A reaction mechanism with four consecutive reactions was considered, and the attack of the nucleophile alcohol on the protonated carbonyl substrate was corroborated as the rate-determining step. A kinetic model with eight independent parameters described with high accuracy the experimental data of 27 reactions with a regression coefficient of 90.9%.

Computational fluid dynamics (CFD): The field of computational fluid dynamics deals with numerical simulations of fluid flows with significant scientific and industrial engineering applications. Fluid flows are governed by the Navier–Stokes equations, which are partial differential equations that describe the conservation of mass and momentum in a Newtonian fluid. These partial differential equations are nonlinear because of the convective acceleration, which captures the change in velocity concerning position. Turbulence, a time-dependent chaotic behavior, is commonly observed in these flows. However, solving the Navier–Stokes equations for turbulent flows can be computationally expensive or even intractable at high Reynolds numbers due to the wide range of spatial and temporal scales involved. Various numerical methods can be employed to solve the Navier–Stokes equations to address this challenge. These methods include finite-difference, finite-volume, finite-element, and spectral methods. Each method discretizes the equations using different orders of approximation. Additionally, turbulence can be simulated at different levels of accuracy and computational cost, depending on the desired fidelity of the results (Vinuesa and Brunton 2022).

Computational fluid dynamics simulations are used to model fluid flow, heat transfer, and mass transfer in biodiesel production reactors. They provide insights into reactor design, mixing efficiency, and heat distribution. Computational fluid dynamics simulations can help optimize reactor configurations, improve mass transfer rates, and ensure efficient heat transfer, enhancing biodiesel production performance. In this context, Huang et al. (2022) presented the design and development of a novel static mixing bioreactor for enzymatic bioprocess, specifically in biodiesel production. To achieve this, the structure of the bioreactor, including unit configuration, aspect ratio, and rotation angle, was designed and optimized using computational fluid dynamics. The researchers used the realizable k-epsilon model, which was proven to be grid-independent with 833,678 hexahedral unstructured grids to improve material mixing. The optimized structure of the bioreactor was determined to be an R-R configuration with an aspect ratio of 1.5 and a rotation angle of 150°. Under these conditions, the researchers optimized the enzymatic production of biodiesel. The optimized process conditions included a static mixer length of 30 cm, a material flow rate of 1.77 m/s, a reaction temperature of 40 °C, the addition of methanol three times, and a molar ratio of 3.4 alcohol to oil with a 10% lipase dose. The results showed that under optimal conditions, the yield of biodiesel reached 81.3% in 1.5 h. Furthermore, even after 12 repeated uses of lipase, the yield remained above 70%. Comparing the static mixer bioreactor with a stirred reactor under the same reaction conditions, the static mixer achieved the same conversion rate (81.3%) in only one-third of the time, demonstrating its excellent mass transfer performance.

Additionally, the study of the specific flow behavior within the microchannel, such as the mixing pattern and the optimization of a microchannel design for biodiesel synthesis, has been extensively conducted using computational fluid dynamics simulations (Mohd Laziz et al. 2020). For better hydrocyclone separation of biodiesel contaminants made from used cooking oil, computational fluid dynamics modeling is used to understand the flow behavior and optimize the hydrocyclone design (Salmanizade et al. 2021). The suitability of the Eulerian and Lagrangian modeling methodologies for various particle concentrations is covered in the above study. The study focuses on the hydrocyclone's structural design and operating factors, such as the diameter of the vortex finder, apex, and cylindrical part length.

Monte Carlo methods (MCM): Monte Carlo is an extremely useful technique for simulating and comprehending random systems and data. It is critical for real-world random system modeling and deterministic numerical computing because it permits stochastic algorithms to escape local optima, allowing for greater search space exploration. The Monte Carlo method also gives insight into randomness by allowing random experiments to be seen on a computer. To evaluate huge and/or high-dimensional data sets, modern statistics increasingly utilize computational methods such as resampling and Monte Carlo methods. Monte Carlo approaches have a theoretical foundation, allowing exact claims on estimator accuracy and algorithm performance. They are utilized in various applications, including industrial engineering and operations research, mathematical programming, autonomous machines and robotics, physical processes and structures, and chemical kinetics (Kroese et al. 2014). Monte Carlo methods involve stochastic simulations to study biodiesel production processes. They can be used to explore the conformational space of molecules, assess the impact of uncertainties in reaction parameters, and simulate the behavior of complex systems. Monte Carlo methods provide statistical information and help understand biodiesel production processes' variability and robustness. To guarantee plant safety and cost-efficiency, prospective investors, governments, engineers, and other stakeholders need additional performance measures, which the Monte Carlo simulation can provide (Abubakar et al. 2015).

Schade and Wiesenthal (2011) applied a risk assessment to the Bio PÓL biofuel model, which predicts the volume of biofuel production in the EU-27 until 2030, using the Monte Carlo simulation approach. The BioPOL model, which simulates the effects of various biofuel support policies on both the production and consumption sides, is a recursive dynamic model. Two simplified policy instances representing a "no tax exemption policy" and a policy introducing a 30% decrease of fossil fuel taxes on biofuels throughout all time stages have been selected as examples. In order to assess the energy use and greenhouse gas emissions from the trap grease-to-biodiesel manufacturing process, Tu and McDonnell (2016) examined the implications of employing a Monte Carlo simulation. Their research emphasized the critical role of incorporating solids in trap grease for anaerobic digestion to achieve significant reductions in both energy consumption and greenhouse gas emissions. The Monte Carlo simulation revealed substantial variations in both life cycle energy consumption and greenhouse gas emissions, primarily due to uncertainties associated with key variables. In comparison to currently popular feedstocks like soybean and algae, trap grease has the potential to be a more energy-efficient and low greenhouse gas emission feedstock under specific circumstances, according to the sensitivity analysis. In restaurants and food processing plants, trap grease builds up in the grease traps as a mixture of water, solids, fats, oils, and greases. Mendecka et al. (2020) considered the energy, economic, environmental, and social effects of the biodiesel production process from used cooking oil using a probabilistic multi-criteria approach that combines Monte Carlo simulation and data reconciliation techniques. The stochastic formulation offers a potent tool to boost the plant's resistance to changes in feed quality. Monte Carlo simulation is used to demonstrate the effect of stochastic optimization in the distribution function of the constraints (Janbarari and Ahmadian Behrooz 2020).

Table 1 presents an insightful comparison of computational techniques extensively used in biodiesel production, outlining their distinctive advantages and limitations. In addition, computational chemistry techniques contribute to the understanding, optimization, and sustainability of biodiesel production processes, facilitating the development of

Table 1 Advantages and disadvantages of widely used computational techniques in biodiesel production

Computational technique	Advantages	Disadvantages	References
Molecular dynamics simulations (MD)	Provides in-depth information on the behavior and interactions of individual molecules Enables the study of complex processes and phenomena at the atomic scale Aids in optimizing reaction conditions and catalyst design for biodiesel production Offers insights into the dynamics and stability of reaction intermediates Allows for the prediction of properties like viscosity and diffusion coefficients	Computationally expensive and requires significant computational resources Limited to relatively short time scales, potentially missing long-term behavior Accuracy relies on the quality of force fields used Challenging to simulate large systems or complex reactions Interpretation of results can be difficult and requires expertise	Filipe and Loura (2022), González et al. (2022), Hwang et al. (2014), Karaytuğ et al. (2021), Yang et al. (2023a)
Density functional theory (DFT)	Provides accurate electronic structure information and energy calculations Predicts reaction pathways and energetics Facilitates the optimization of reactant and catalyst structures for biodiesel production Less computationally demanding compared to higher-level quantum mechanical methods Can calculate thermodynamic properties of reactants and products	Limited to small systems due to computational costs Potential errors due to functional approximations Inaccurate treatment of dispersion forces can be significant in some systems It may not capture certain dynamic effects or long-range interactions Requires expertise to interpret and validate the results	Chen et al. (2023), dos Santos et al. (2011), Kim et al. (2022), Li et al. (2015), Li et al. (2018), Ning et al. (2020), Wang et al. (2020b)
Quantum mechanics/molecular mechanics (QM/MM)	Combines the accuracy of quantum mechanical calculations with the efficiency of molecular mechanics Particularly suitable for studying reactions in complex environments Can model large systems like enzymes and solvents Provides insights into reaction mechanisms and catalytic processes Accounts for solvent effects and molecular interactions	Computational cost increases with system size and complexity Accuracy depends on the quality of force fields and quantum mechanical methods used It may require simplifications or approximations to make calculations feasible Requires careful selection of the quantum mechanics/molecular mechanics interface region Interpretation of results can be challenging due to the complexity of combined calculations	Cui et al. (2021a), Kumar et al. (2023a), Osman et al. (2023b), Qiu et al. (2012), Senn and Thiel (2009), Taylor et al. (2022)
Kinetic modeling	Provides insights into reaction rates and time-dependent behavior Predicts optimal reaction conditions and catalysts for biodiesel production Optimizes process parameters to maximize yield and selectivity Simulates large-scale biodiesel production systems Investigate complex reaction networks	Requires accurate kinetic data, which may be limited for some reactions Complexity increases with the number of reactions and species involved It may require assumptions and simplifications for computational feasibility Challenging parameter estimation requiring experimental data Crucial to validate the model against experimental results, but it can be time-consuming and expensive	Chang et al. (2021), Gaurav et al. (2019), Hazrat et al. (2022), Pasha et al. (2021b), Raheem et al. (2020), Serrano et al. (2015), Sharma et al. (2019a)

Table 1 (continued)

Computational technique	Advantages	Disadvantages	References
Computational fluid dynamics (CFD)	Predicts fluid flow patterns, mixing, and heat transfer in biodiesel production reactors Optimizes reactor design and process parameters Provides insights into mass transfer and reaction kinetics Identifies potential reactor scale-up issues Reduces the need for expensive and time-consuming experimental trials Improves the separation of biodiesel impurities prepared from waste	Requires extensive computational resources and time Accuracy depends on the quality of fluid flow and reaction models used It may require simplifications, such as assuming idealized geometries or neglecting certain effects Requires validation against experimental data for reliability Complex reactor geometries and multiphase systems pose challenges for accurate simulations	de Boer and Bahri (2015), Huang et al. (2022), Krishnasamy and Bukkarapu (2021), Quiroz-Pérez et al. (2019), Santana et al. (2022)
Monte Carlo methods (MCM)	Simulates large systems with numerous degrees of freedom Provides statistical information on the distribution of molecular properties Explores conformational spaces and reaction pathways Estimates thermodynamic properties like free energies and partition coefficients Investigates rare events and equilibrium properties	Sampling efficiency can be challenging, especially for high-dimensional systems Requires significant computational resources for accurate results Sensitivity to the choice of simulation parameters and algorithms Accuracy depends on the quality of force fields and sampling methods used Interpretation of results may require expertise in statistical mechanics and data analysis	An et al. (2021), Arora and Singh (2020), Kannan and Diwekar (2023), Kroese et al. (2014), Oke et al. (2021b)

Molecular dynamics simulations offer detailed molecular insights but are computationally expensive. Density functional theory provides accurate energycalculations but struggles with large systems; meanwhile, quantum mechanics/molecular mechanics methods combine accuracy and efficiency but are more expensive for complex systems. Kinetic modeling predicts reaction rates but needs precise kinetic data. Computational fluid dynamics forecasts fluid flow but demands substantial computational resources. Monte Carlo methods simulate large systems but encounter sampling efficiency challenges. These techniques provide distinct advantages and challenges, crucial for informed computational strategies in biodiesel production efficient and environmentally friendly methods for renewable fuel production.

Applications of computational chemistry

Catalyst design

Catalyst design may be defined as the systematic application of the knowledge currently available for selecting a catalyst in a specific reaction. It is a difficult undertaking since there aren't many precise and specific techniques for developing and designing catalysts for certain reaction systems; instead, trial and error are used most of the time. A range of catalysts can often be expected to work well for a certain process and can only be verified by tests. By correctly implementing the catalyst design technique, the number of catalysts that must be tested can be decreased. It is frequently advised in catalyst design to modify the currently available catalyst for a specific process based on the user's demands rather than creating a new catalyst material. Designing a completely new catalyst and modifying an existing catalyst for a particular purpose involves significantly different techniques. Technical, economic, and environmental assessments are required before constructing a wholly unique catalyst. The designed catalysts should be economically viable, environmentally safe, and technically possible. But if a catalyst must be created for an already-existing mechanism, the creation might be based on some chemical principles (Arun et al. 2015).

Computational design of catalysts necessitates mechanistic insights into reaction chemistry, catalyst structure and evolution under reaction conditions, and methods for quick screening of prospective catalysts (Varghese 2019). Designing and improving catalysts for the transesterification reaction required to produce biodiesel from waste can be done using computational chemistry. Researchers can find extremely effective catalysts that speed up the reaction and increase biodiesel yield by modeling and simulating the interactions between catalysts and reactants at the molecular level. Computational chemistry allows researchers to study and analyze the interactions between catalysts and reactants at the molecular level. This enables the identification and designing of highly effective catalysts that can accelerate the reaction rate and improve the overall yield of biodiesel.

An effective approach for forecasting and creating catalysts, understanding their roles, and anticipating the outcomes of the chemical reactions they facilitate, including activity, selectivity, and potential applications, involves combining computational chemistry and catalysis. Transition metal, organo-, photo redox, and surface catalysis have all been used to explain the activity and selectivity of the catalyst function as well as the related reaction mechanisms in recent decades. This has been made possible by advancements made in the applied theoretical framework involving density functional theory and solvation models (Stiriba 2023). Today, computational chemistry is frequently used to support the interpretation of spectroscopic catalytic characterization, the prediction of the relative stability of various adsorbed species on catalytic surfaces, and the simulation of reaction pathways, useful for cross-validating proposed catalytic mechanisms based on kinetic and spectroscopic measurements. It is expected that computational approaches and theory will continue to make it easier to comprehend the links between catalyst composition, reactivity, and structure, which is essential for directing the design of engineered catalytic materials.

The design of catalytic processes affects the content and characteristics of biofuels, and engine operating conditions affect fuel needs. An inefficient design cycle of catalyst design, manufacture of biofuel candidates, fuel property testing, potentially low fuel quality, restart, and repeat is involved in developing approved "drop-in" biofuels (Kim et al. 2020). This study applied a fuel-property-first paradigm, which uses computational screening techniques to link desired fuel attributes to chemical structures. By linking fuel qualities to catalyst design and process development at the beginning of the design cycle, this strategy intends to reduce failures in creating biofuels with desirable attributes.

Overall, computational chemistry offers a powerful toolset for understanding and optimizing biodiesel production from waste. It enables the design of efficient catalysts, optimization of reaction conditions, characterization of biodiesel properties, and investigation of degradation mechanisms. By leveraging computational methods, researchers can accelerate the development and commercialization of sustainable biodiesel production processes, contributing to the advancement of renewable energy and waste.

The following areas have been chosen for future development in computational catalysis to accomplish this goal (Bravo-Suárez et al. 2013):

Better and more accurate techniques for cluster analysis at length and time scales play a crucial role in catalysis. For example, current density functional theory exhibits energetic associated errors in the range of 10 kJ/mol, highlighting the need for improvement. Enhancing these techniques is essential to enhance the prediction powers of computational methods, specifically in the context of catalyst selectivity. Another important aspect is incorporating solvent effects into simulations, enabling the modeling of spectra and the forecast of the stability of surface/cluster complexes. Computational detection of non-equilibrium structures poses a challenge, while surface phase composition can undergo changes during reactions under various gas and/or liquid phase compositions. Additionally, the impact of solvents on reactivity cannot be disregarded.

In the case of complicated systems with extended surfaces like transition metal oxides, carbides, nitrides, and sulfides, the existing methods or correlations between reactivity and kinetic characteristics, such as theoretical reactivity descriptors, are currently absent. This knowledge gap hampers the understanding of these systems and impedes the optimization of catalysts based on such materials. However, advancements have been made in developing more effective techniques and related computer programs for researching complicated industrial multicomponent catalysts. These catalysts encompass various components, including flaws, promoters, and two- or three-phase systems. The development of these techniques and software tools has facilitated deeper insights into the behavior and performance of such catalysts, ultimately aiding in their design and optimization for industrial applications. Strategies for predicting the synthesis of catalysts include incorporating weak forces like van der Waals interactions and examining the changes in catalyst precursors and reaction intermediates. These strategies allow researchers to consider subtle intermolecular interactions and provide a comprehensive understanding of catalyst synthesis. By accounting for these factors, researchers can improve their ability to predict and optimize the synthesis of catalysts.

Catalyst deactivation analysis

Understanding catalyst deactivation mechanisms and devising ways to build stable catalysts are just as essential as catalytic selectivity and activity studies, yet deactivation processes are frequently disregarded in academic studies. Poisoning, fouling, sintering, crushing, catalyst surfaces interacting with a gas to generate volatile chemical, and inactive phase development on catalyst surfaces following interaction with vapor, support, or promoter are the six types of deactivation mechanisms identified by Bartholomew (2001). Modeling is important in understanding catalyst deactivation processes, aiding process improvement, and thereby improving biofuel commercialization (Adkins et al. 2021; Chen et al. 2021b; Lattanzi et al. 2020; Pecha et al. 2021). Computational chemistry can assist in the analysis of catalyst deactivation mechanisms during biodiesel production. By studying the interactions between catalysts and contaminants present in waste feedstocks, researchers can identify factors contributing to catalyst deactivation and develop strategies to mitigate or prevent it, thereby extending catalyst lifespan and improving process economics.

Reaction optimization

Computational chemistry makes the optimization of reaction conditions, including temperature, pressure, and solvent composition, possible (Basdogan et al. 2020; Mendis et al. 2022). Researchers may examine the influence of various factors on the reaction kinetics and find the ideal conditions that optimize waste conversion into biodiesel using molecular simulations. Gong et al. (2020) focused on the optimization of the static mixer structure for enzymatic synthesis of biodiesel from waste cooking oil using computational fluid dynamics modeling. The optimal static mixer consists of six mixer units with a length-diameter ratio of 1.5. The enzymatic synthesis of biodiesel was conducted between waste cooking oil and methanol by transesterification and esterification. The reaction conditions were also optimized in this designed static-mixed reactor. Under optimal conditions, the reaction time can save half-time when compared with the traditional stirred reactor, indicating that the static mixer has higher production efficiency.

Reactor design and optimization

Computational chemistry can assist in the design and optimization of biodiesel production reactors. Through computational fluid dynamics simulations, researchers can model the fluid flow, heat transfer, and mass transfer within the reactor. This information helps optimize reactor geometry, configuration, and operating conditions to achieve efficient mixing, heat distribution, and mass transfer, resulting in improved biodiesel production. In addition, computational chemistry can provide insights into reactor scale-up for biodiesel production. By simulating reactions at different scales, researchers can evaluate the impact of reactor size on reaction kinetics, heat transfer, and mass transfer. This knowledge guides the scaling-up process and helps design larger-scale reactors that maintain optimal performance and productivity.

In recent years, the development of microreactors as a type of reactor used to synthesize biodiesel has attracted attention (Tiwari et al. 2018). Researchers and industry experts use modeling and simulation to optimize machinery and procedures in traditional-size operations. In contrast to typical scale processes, modeling and simulation in microfluidics are still relatively new, making the literature on biodiesel production even rarer. From the perspective of modeling and microreactor simulations, the study by Santana et al. (2019) explores biodiesel synthesis in microreactors.

Stability assessment

Biodiesel offers advantages but faces storage stability issues, poor oxidation stability, and limited energy availability, affecting its widespread commercialization in various countries (Moreira et al. 2022). Several factors can influence the stability of biodiesel, including auto-oxidation, thermal decomposition or thermal fluctuations, water absorption, biodegradation with microbial growth, storage conditions, metal contamination, and the presence and absence of additives (Jakeria et al. 2014). Computational chemistry plays a role in understanding biodiesel's stability and degradation mechanisms. By studying molecular structures and analyzing reaction pathways, researchers can identify potential degradation pathways and develop strategies to enhance biodiesel products' stability and shelf life.

Waste feedstock analysis

Computational chemistry can aid in the analysis and characterization of waste feedstocks for biodiesel production. By studying the chemical composition and properties of different waste oils and fats, researchers can determine their suitability for biodiesel production and optimize the selection of feedstock sources. Computational chemistry can play a crucial role in optimizing the selection of waste feedstock sources for biodiesel production by providing insights into their chemical composition and properties. Here's how computational chemistry can assist in this process:

Chemical analysis: Computational chemistry can be employed to analyze the chemical composition of different waste feedstocks. By simulating the molecular structures and properties of the components present in the feedstocks, researchers can identify the types and quantities of fatty acids, triglycerides, and other relevant compounds. This analysis helps in assessing the potential of a particular waste feedstock for biodiesel production (Achinas and Euverink 2016; Li et al. 2021; Long et al. 2022).

Property prediction: Computational chemistry enables the prediction of important properties of waste feedstocks. Researchers can use computational methods to estimate viscosity, density, molecular weight, and oxidative stability properties. These predictions aid in evaluating the suitability of a waste feedstock for biodiesel production and comparing it with other potential sources (Ahmad et al. 2023b; Canakci et al. 2009; García et al. 2010).

Reaction modeling: Computational chemistry can simulate and model the transesterification reaction of different waste feedstocks with alcohol to produce biodiesel. Researchers can assess the feasibility and efficiency of using specific feedstocks by studying the reaction kinetics, conversion rates, and yield predictions. This information helps identify the most promising waste feedstock sources for biodiesel production (Anitescu and Bruno 2012; Baioni e Silva et al. 2023; Silitonga et al. 2020).

Contaminant analysis: Waste feedstocks for biodiesel production often contain contaminants, such as water, free fatty acids, and impurities. Computational chemistry can assist in analyzing the impact of these contaminants on the reaction kinetics and efficiency. By modeling the interactions between contaminants and catalysts or reactants, researchers can determine the potential challenges and develop strategies to mitigate their negative effects (Yadav et al. 2021).

Environmental impact assessment: Computational chemistry can also be used to assess the environmental impact of different waste feedstock sources. Researchers can estimate factors such as energy consumption, greenhouse gas emissions, and waste generation by modeling and simulating the production processes associated with each feedstock. This information aids in selecting feedstock sources that have lower environmental footprints and align with sustainability goals (Azadi et al. 2014; Caldeira et al. 2019; Pasha et al. 2021a).

Process scale-up

On a laboratory scale, biodiesel has been produced via acid transesterification, alkali transesterification, acid–alkali transesterification, enzymatic transesterification, and supercritical alcohol transesterification (Tabernero et al. 2012). Zhang et al. (2003) demonstrated a large-scale simulation of several of the previously described acquiring processes. The number of industrial bioprocesses is continuously increasing because of increased market demand for bulk production of chemicals, biofuels, materials, nutrition components, and healthcare goods. This need is accompanied by the pressing need to shift from a fossil-based to a bio-based economy. Scaling up from laboratory to large-scale requires verification of process and product quality comparability, which generally follows a time-consuming, lab-intensive, sequential scale-up strategy. This is based on expert empiricism and does not account for possible strain changes (Wang et al. 2020a).

Olkiewicz et al. (2016) evaluated the economic feasibility of biodiesel production from municipal primary sewage sludge, a promising lipid feedstock for biodiesel production. The study focuses on eliminating high water content before lipid extraction, which is the main limitation of scaling up. The study uses computational tools to model the process scale-up and different configurations of lipid extraction to optimize this step, which is the most expensive. The operational variables with a major influence on the cost were extraction time and the amount of solvent. The optimized extraction process had a break-even price of biodiesel of 1232 USD per ton, being economically competitive with the current cost of fossil diesel. Understanding how to scale up biodiesel manufacturing systems may be gained through computational chemistry. The behavior of reaction systems at greater sizes may be simulated and modeled, which allows researchers to foresee problems and improve process parameters for efficient and economical production.

Reaction mechanism elucidation and molecular dynamics simulations:

Computational chemistry can be used to better understand the complex chemical pathways involved in producing biodiesel from waste materials. Researchers can better understand the underlying chemistry and suggest methods for increasing reaction efficiency by looking at the step-by-step routes and identifying the rate-determining phases. In this context, the computational chemistry study showed that the interaction mechanism between the optimized catalyst and stearic acid was preferable between tin(IV) oxide (SnO_2) active sites and the carbonic group of stearic acid (Ibrahim 2021). In addition, computational chemistry techniques, such as molecular dynamics simulations, can provide insights into the behavior and interactions of biodiesel molecules with other components, such as enzymes or additives. This understanding can aid in developing more efficient and selective processes for biodiesel production (Hwang et al. 2014).

In conclusion, the use of computational chemistry is crucial in the progress of biodiesel production from waste, as it provides valuable tools for catalyst development, reaction improvement, and process enhancement. It allows for a detailed understanding at the molecular level, aiding in the selection and design of effective catalysts and optimized reaction conditions. Computational simulations are useful in exploring complex reaction mechanisms, contributing to a better understanding of the intricate pathways involved in biodiesel synthesis. Furthermore, these techniques support reactor design, analysis of waste feedstocks, and the scaling up of processes, which are essential for the successful application of laboratory findings in large-scale industrial settings. As computational methodologies continue to advance, they offer promising opportunities for the sustainable and efficient production of biodiesel from diverse waste sources.

Machine learning and data mining

In the past 10 years, machine learning has experienced tremendous growth as a crucial data processing tool. This has substantially expanded artificial intelligence's problem-solving capabilities. Machine learning is a group of advanced data analysis techniques that find patterns between characteristics in a data set and make predictions when faced with new inputs. These techniques are founded on the concepts of probability and, statistics, and mathematics (Wang et al. 2022b). Data mining is a discipline closely related to machine learning and knowledge areas such as statistics. The development of data mining as an autonomous discipline has been allowed by the increase in size and structuring of the data to which these techniques are applied (Taranto-Vera et al. 2021).

Machine learning surpasses conventional mathematical and statistical models in the manufacturing sector in effectiveness. This is due to the limitations of traditional models in comprehending intricate relationships between data characteristics and predicting feature values for new samples. Consequently, the manufacturing industry has increasingly embraced machine learning techniques that are widely utilized in various scientific domains. Leveraging intelligent data analysis is of great value as it allows companies to gain fresh insights and attain a crucial competitive edge. Thus, the application of machine learning and data mining methods in manufacturing has become well-established (Dogan and Birant 2021).

The main machine-learning approaches may be broken down into two basic categories: supervised learning and unsupervised learning (Taranto-Vera et al. 2021). Although clustering problems are more frequent in unsupervised learning, classification problems are a common problem in supervised learning. While k-means is the most used clustering technique, classification algorithms like artificial neural networks (ANNs), support vector machines (SVMs), and decision trees are also extensively utilized (Ahmadinia et al. 2013; Dogan and Birant 2021; Parvin et al. 2015). Artificial intelligence and machine learning have recently been used to successfully implement statistical modeling in various applications. To optimize the production of biodiesel, these models have shown themselves to be trustworthy and dependable. Machine learning techniques for finding useful findings from experimental outputs are the most important advancements that have impacted many scientific domains (Almohana et al. 2022; Wang et al. 2021; Xing et al. 2021a). Table 2 summarizes the advantages and disadvantages of artificial intelligence and machine learning-based models typically employed in the prediction of biodiesel process and fuel properties.

Methodology for machine learning-based biodiesel production prediction from waste

The methodology for machine learning-based biodiesel production prediction from waste encompasses several key steps, which can be summarized as follows:

Dataset collection: Compile a complete dataset of waste feedstocks, biodiesel production parameters, and associated biodiesel attributes. Include a variety of waste sources and a wide range of operational circumstances (Cheng et al. 2016; Gupta et al. 2021).

Data preprocessing: Clean the dataset by removing any missing or erroneous values and perform necessary transformations or normalization to ensure consistency and quality (Ahmad et al. 2023b).

Table 2 Advantages and disadvantages of artificial intelligence and machine learning-based models typically employed in the prediction of biodiesel process and fuel properties

Model type	Advantages	Disadvantages	References
Artificial neural networks (ANNs)	Artificial neural networks are capable of handling complex, nonlinear relationships in data They possess the ability to learn and adapt to new patterns and data Artificial neural networks can capture both local and global relationships in biodiesel production data They are suitable for handling large datasets and input features with a high number of dimensions With proper training and optimization, artificial neural networks can provide accurate predictions	Artificial neural networks require a substantial amount of training data to achieve good performance Training artificial neural networks can be computationally demanding and time-consuming Artificial neural networks are often considered models that lack interpretability, making it challenging to understand their underlying mechanisms Overfitting can occur if the model is too complex or if the training data is insufficient Artificial neural networks may face difficulties with extrapolating to unseen data or situations beyond the training range	Aghbashlo et al. (2021), Ahmad et al. (2023b), Dumitru et al. (2013), Mohaghegh (2000), Najafi et al. (2007), Rahmanifard and Plaksina (2019), Raj et al. (2021), Sewsynker-Sukai et al. (2017), Xing et al. (2021b)
Support vector machines (SVMs)	Support vector machines are effective in handling biodiesel data with a high number of dimensions They can handle both linear and nonlinear relationships by utilizing appropriate kernel functions Support vector machines have a strong theoretical foundation and guarantee global optimization Support vector machines are less susceptible to overfitting, even when the training data is limited Support vector machines can handle both classification and regression tasks in biodiesel prediction	Support vector machines can be computationally expensive for large datasets Proper selection of kernel functions and hyperparameter tuning is crucial for achieving good performance with support vector machines Support vector machines may be sensitive to the choice of hyperparameters and can be challenging to interpret Support vector machines can struggle when dealing with imbalanced class distributions in datasets Support vector machines may not perform well in situations where the data is noisy or overlaps	Anguita et al. (2010), Cheng et al. (2016), Corral Bobadilla et al. (2018), Karamizadeh et al. (2014), Maltarollo et al. (2019), Said et al. (2022)
Multi-layer perceptron neural network (MLPNN)	Multi-layer perceptron neural network can model complex nonlinear relationships in biodiesel production data They are capable of handling both classification and regression tasks Multi-layer perceptron neural network can learn and generalize from large and diverse datasets They can capture both local and global dependencies in the data With appropriate architecture design and training, a multi-layer perceptron neural network can provide accurate predictions	Careful selection of the number of hidden layers and neurons is necessary for multi-layer perceptron neural network, which can be challenging Training multi-layer perceptron neural network can be computationally demanding and time-consuming Overfitting can occur if the model is too complex or if the training data is insufficient Interpreting multi-layer perceptron neural network can be difficult due to their black-box nature Multi-layer perceptron neural network may face difficulties with extrapolating unseen data or situations beyond the training range	Ahmad et al. (2023b), Ditzler et al. (2015), Jin et al. (2022), Park and Lek (2016), Patil-Shinde et al. (2023)

Table 2 (continued)

Model type	Advantages	Disadvantages	References
Radial basis function neural network (RBFNN)	Radial basis function neural networks are capable of approximating complex nonlinear functions They have a strong mathematical foundation and can provide accurate predictions Radial basis function neural network can handle both regression and classification tasks They are less prone to overfitting, especially when appropriate regularization techniques are applied Radial basis function neural network can handle biodiesel data with a high number of dimensions and is computationally efficient	Determining the optimal number and placement of radial basis functions can be challenging for radial basis function neural network Training radial basis function neural network can be computationally expensive, particularly with large datasets Interpreting radial basis function neural network can be difficult due to their black-box nature Radial basis function neural network may face difficulties with extrapolating unseen data or situations beyond the training range Radial basis function neural network may not perform well with datasets that have imbalanced class distributions	Ahmad et al. (2023b), Can et al. (2022), Nabipour et al. (2020), Yu et al. (2011)
Adaptive neuro-fuzzy inference system (ANFIS)	Adaptive neuro-fuzzy inference system combines neural networks and fuzzy logic, offering a hybrid modeling approach They can incorporate both numerical and linguistic information in biodiesel predictions Adaptive neuro-fuzzy inference system models are transparent, enabling interpretable decision-making They handle both regression and classification tasks effectively Adaptive neuro-fuzzy inference system models can learn from data and adapt their structure to enhance performance	Training adaptive neuro-fuzzy inference system models can be computationally demanding, particularly with large datasets Determining optimal fuzzy rules and membership functions can be challenging Adaptive neuro-fuzzy inference system models may not perform well with imbalanced class distributions in datasets Overfitting can occur if model complexity is not properly controlled Adaptive neuro-fuzzy inference system models may struggle with extrapolating to unseen data or situations beyond the training range	Ajala et al. (2023), Aribarg et al. (2012), Jisieike et al. (2023), Kartal and Özveren (2022), Khan et al. (2023)
Extreme learning machine (ELM)	Extreme learning machine models have rapid training times compared to traditionalneural networks They efficiently handle large datasets Extreme learning machine models are less prone to overfitting, even with limited training data They approximate complex nonlinear relationships in biodiesel data Extreme learning machine models provide competitive prediction accuracy with lower computational requirements	Extreme learning machine models may not generalize well to unseen data compared to some other algorithms The absence of iterative training in extreme learning machines limits its ability to fine-tune and adapt to complex datasets Extreme learning machine models may struggle with datasets that have imbalanced class distributions Interpretation of extreme learning machine models can be challenging due to their black-box nature Extreme learning machine models may not perform well with datasets that contain high levels of noise or outliers	Ahmad et al. (2023b), Deng et al. (2009), Mujtaba et al. (2020), Silitonga et al. (2020)

Table 2 (continued)

Model type	Advantages	Disadvantages	References
Kernel extreme learning machine (KELM)	Kernel extreme learning machine combines the advantages of extreme learning machine with the flexibility of kernel methods They handle nonlinear relationships using appropriate kernel functions Kernel extreme learning machine models have fast training times and efficiently handle large datasets They are less prone to overfitting, even with limited training data Kernel extreme learning machine models provide competitive prediction accuracy and handle high-dimensional biodiesel data	Proper selection of kernel functions and hyperparameter tuning is crucial for achieving good performance Kernel extreme learning machine models may be sensitive to the choice of hyperparameters and challenging to interpret They may struggle with datasets that have imbalanced class distributions Interpretation of kernel extreme learning machine models can be challenging due to their black-box nature Kernel extreme learning machine models may not perform well with datasets that contain high levels of noise or outliers	Forootan et al. (2022), Peng et al. (2017), Wong et al. (2015)
Least squares support vector machine (LS-SVM)	Least squares support vector machine models, have a solid theoretical foundation and ensure global optimization They handle both linear and nonlinear relationships using appropriate kernel functions Least squares support vector machine models that are less prone to overfitting, even with limited training data They provide accurate predictions and efficiently handle high-dimensional biodiesel data Least squares support vector machine models handle both regression and classification tasks in biodiesel prediction	Least squares support vector machine models can be computationally expensive, especially for large datasets They may struggle with datasets that have imbalanced class distributions Interpretation of least squares support vector machine Models can be challenging due to their black-box nature Least squares support vector machine models may not perform well with datasets that contain high levels of noise or outliers	Ahmad et al. (2023b), Chen and Zhou (2018), Liu and Baghban (2017), Nabipour et al. (2020), Razavi et al. (2019)
Bidirectional recurrent neural network (BRNN)	Bidirectional recurrent neural network captures past and future dependencies in sequential biodiesel data They excel in modeling temporal relationships and time series data Bidirectional recurrent neural network handles variable-length input sequences They provide accurate predictions by utilizing both forward and backward information flow Bidirectional recurrent neural network is suitable for biodiesel prediction tasks involving sequential data, such as time-dependent process variables	Training bidirectional recurrent neural network can be computationally expensive, especially with large and complex sequential datasets Determining the optimal architecture and hyperparameters for bidirectional recurrent neural network can be challenging Bidirectional recurrent neural network may struggle with long-range dependencies in the data Interpretation of bidirectional recurrent neural network can be difficult due to their complex architecture and black-box nature Overfitting can occur if the model is too complex, or the training data is insufficient	Ankobea-Ansah and Hall (2022), Dharmalingam et al. (2023), Kolakoti et al. (2023), Ticknor (2013)

Table 2 (continued)

Model type	Advantages	Disadvantages	References
Alternating model tree (AMT)	The alternating model tree algorithm is designed specifically for biodiesel production modeling and prediction It incorporates domain-specific knowledge and heuristics into the modeling process The alternate model tree handles both numerical and categorical variables in biodiesel prediction tasks The algorithm provides transparency and interpretability in decision-making Alternating model tree effectively handles complex relationships and interactions among variables in biodiesel production	The performance of the alternating model tree algorithm heavily relies on the quality and relevance of domain-specific knowledge and heuristics Alternating model tree may not perform as well as more general-purpose machine learning algorithms in certain scenarios It may require manual intervention and expert input to finetune the model and incorporate domain knowledge The scalability of the alternating model tree algorithm to larger datasets and high-dimensional feature spaces may be limited Alternating model tree may not generalize well to unseen data or situations outside the training range if the domain-specific knowledge is insufficient or incomplete	Ahmad et al. (2023b), Cui et al. (2021b), Moayedi et al. (2020), Sok et al. (2016)

Artificial neural networks exhibit adaptability and versatility, but they necessitate abundant training data and significant computational resources. Support vector machines excel in strong optimization, yet they are sensitive to parameters and class imbalances. While multi-layer perceptron neural networks and radial basis function neural networks ensure accuracy, they demand meticulous architecture design. Adaptive neuro-fuzzy inference systems offer interpretability with hybrid modeling but are computationally intensive. In contrast, extreme learning machines, kernel extreme learning machines, and bidirectional recurrent neural networks provide rapid training but might lack generalization capacity. Finally, the alternating model tree algorithm incorporates domain-specific knowledge but might need manual intervention and lacks scalability with larger datasets

Feature selection: Determine the key characteristics or factors that substantially influence waste-to-biodiesel production. To choose the most informative characteristics, statistical analysis, domain expertise, or feature ranking algorithms may be used (Ahmad et al. 2023a; Balabin and Smirnov 2011).

Model selection: Choose appropriate machine learning algorithms for biodiesel production prediction from waste. Consider regression models, such as linear regression, support vector regression, or decision tree regression, as well as more advanced techniques like random forests, gradient boosting, or neural networks (Bobadilla et al. 2018).

Model training: Split the dataset into training and validation sets. Train the selected machine learning models using the training data, adjusting hyperparameters and optimizing model performance through techniques like cross-validation and grid search (Fangfang et al. 2021; Sharon et al. 2012).

Model evaluation: Assess the performance of the trained models using appropriate evaluation metrics, such as mean squared error (MSE), root mean squared error (RMSE), or coefficient of determination (R-squared). Compare the performance of different models to select the most accurate and reliable one (Fangfang et al. 2021; Freitas et al. 2011; Kumar et al. 2023b).

Model optimization: Improve the prediction performance of the chosen model by modifying hyperparameters or using techniques such as regularization. Consider ensemble learning or model stacking to integrate many models and improve overall accuracy (Almohana et al. 2022; Bobadilla et al. 2018).

Predictive modeling: Use the learned machine learning model to forecast biodiesel production from waste for unseen data points. Apply the algorithm to new waste feedstocks to determine their potential for biodiesel generation (Chuck et al. 2009; Freitas et al. 2011; Oke et al. 2021a).

Model deployment: Integrate the trained model into a user-friendly software or web application that allows users to input waste feedstock characteristics and obtain predictions of biodiesel production. Ensure the application is scalable and can handle large volumes of data (Sharma et al. 2023; Tozzi and Jo 2017).

Continuous improvement: Regularly update the model with new data and retrain it to capture evolving trends and improve prediction accuracy. Monitor the model's performance and gather user feedback to identify areas for further refinement or enhancement (Bachinger et al. 2021).

Ethical considerations: Consider the ethical implications of using machine learning for biodiesel production from waste. Ensure data privacy and security, address potential biases in the data or models, and adhere to relevant regulatory and ethical guidelines in the development and deployment of the system (Hagendorff and Meding 2023; Samuel et al. 2020).

Machine learning techniques can be employed to analyze large datasets generated from experimental or computational studies. Machine learning algorithms can identify patterns, correlations, and trends in the data, aiding in process optimization, catalyst design, and property prediction, as illustrated in Fig. 3. Data mining techniques can also assist in extracting useful information from existing databases and literature. Machine learning and data mining techniques can play a crucial role in the production of biodiesel from waste materials by optimizing processes, improving feedstock selection, enhancing quality control, and supporting sustainability efforts (Aghbashlo et al. 2021; Sharma et al. 2023). Table 3 illustrates the different artificial intelligence-based models used for the production of biodiesel from different waste feedstock.

Applications of machine learning and data mining

Here are some specific applications of machine learning and data mining in biodiesel production from waste:

Feedstock characterization and selection: Machine learning algorithms can analyze large volumes of data on waste feedstocks, including their composition, properties, and availability. By training models on this data, machine learning can identify the most suitable feedstocks for biodiesel production based on their lipid content, moisture levels, impurities, and other factors. This helps optimize feedstock selection and ensures efficient resource utilization. Making mathematical correlations between feedstock composition and quality parameters with reasonable accuracy could have several benefits on scientific plans. It could help estimate the ability of a feedstock to produce a good quality of biodiesel before undergoing time and money-consuming characterization. It could also help determine appropriate treatment strategies for feedstock to improve biodiesel properties (Mairizal et al. 2020). In the case of feedstock characterization, Multiple non-linear regression and artificial neural networks were used by Tchameni et al. (2019) to forecast the rheological characteristics of used vegetable oil for the generation of biodiesel.

Process optimization and reaction kinetics modeling: Machine learning algorithms can be applied to optimize process parameters such as temperature, pressure, catalyst concentration, and reaction time. Machine learning models can identify optimal operating conditions that maximize yield and minimize energy consumption by analyzing historical process data and biodiesel yield. In addition, machine learning techniques can be employed to model the kinetics of the biodiesel production process. Machine learning models can predict reaction rates and conversion levels by analyzing reaction time, temperature, and other variables, aiding in process optimization and control. In order to enhance the production of biodiesel from a feedstock,

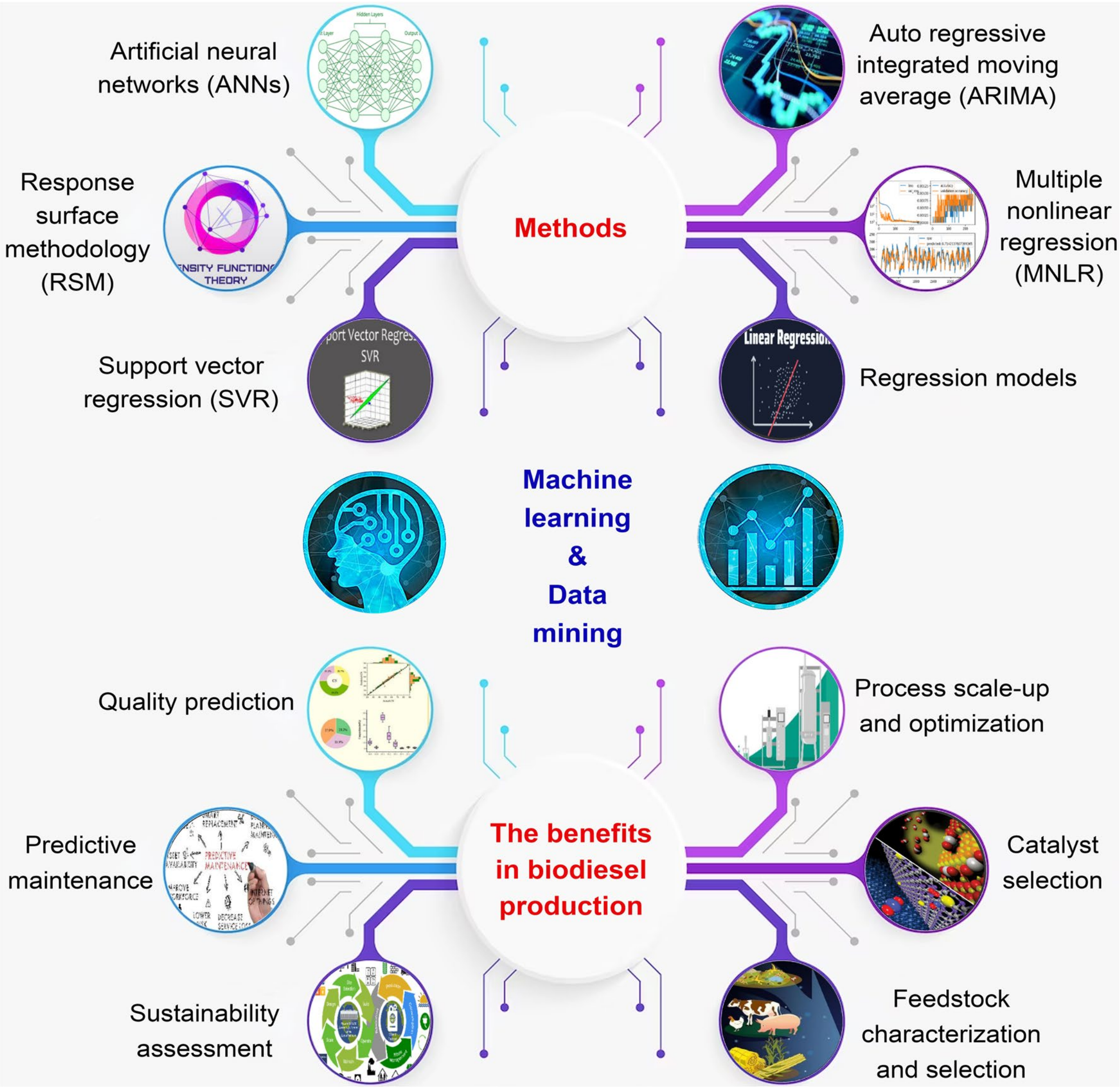

Fig. 3 Machine learning methods and their application in biodiesel production. The figure offers an extensive portrayal of machine learning's vital involvement in various crucial aspects of biodiesel production. Across feedstock characterization and selection, machine learning demonstrates proficiency in identifying and assessing the most suitable feedstock for biodiesel production. In process optimization and reaction kinetics modeling, this technology showcases its capability to enhance production efficiency and accurately predict reaction rates. Moreover, the figure delineates quality prediction, catalyst selection, and sustainability assessment, emphasizing the pivotal role of machine learning in ensuring top-notch product quality, efficient catalyst selection, and evaluating environmental impact. Additionally, it addresses predictive maintenance, highlighting how machine learning facilitates proactive equipment upkeep and process scale-up and optimization, elucidating its contribution to refining and scaling production processes for maximum efficiency

several machine-learning regression models were developed (Abdelbasset et al. 2022). Several operational factors, including reaction time, reaction temperature, the molar ratio of oil to alcohol, catalyst yield percentage, and others, may strongly impact the transesterification process's ability to produce biodiesel. Numerous tests must be conducted to optimize the numerous transesterification reaction variables, as well as the use of an appropriate statistical technique that can forecast the influence of every factor on the reaction and its interactions. For the optimization of the process variables to achieve the desired output with fewer tests, the response surface methodology technique has been widely employed. The number of tests is carried out using a variety of experimental designs, including the Taguchi experimental design, factorial design, central composite design, and box-banging design (Gupta et al. 2021). Waste cooking oil was considered the reaction's feedstock, and a heterogenous catalyst was considered. The model considered four distinct input variables: reaction temperature, time, catalyst loading, and methanol to oil molar ratio, with the predicted output being the production yield (%). The maximum production yield was sought by determining the input parameters' ideal values.

Almohana et al. (2022) used three ensemble models: Huber regression, decision trees, and gaussian process regression to optimize biodiesel production using cooking oil as a feedstock. Batch reaction experiments with four input parameters, reaction temperature, reaction duration, catalyst loading, and methanol to oil ratio, were used in the optimization process. These models, which have been used in various applications, have shown encouraging results in estimating the output of biodiesel production. Sultana et al. (2020) focused on applying data mining techniques to optimize the synthesis of non-edible papaya seed waste oil for biodiesel production. Thus, several soft computing or data mining techniques, including support vector regression, artificial neural network, and response surface methodology, may be utilized for predicting oil yields from used papaya seeds after solvent extraction. According to the results, the support vector regression model outperformed the artificial neural network and response surface methodology models in terms of several performance-measuring factors when it came to estimating oil yields. Oil yields increase as extraction time increases but decrease as particle size increases. A support vector regression and crow search algorithm-based interface were implemented to discover the global optimum set. Moradi et al. (2013) investigated the best conditions for producing biodiesel from soybean oil, as well as the use of artificial neural networks to predict the yield of the biodiesel. The methanol-to-oil molar ratio, the amount of catalyst, and the reaction temperature were the variables that were examined. It was determined that a 9:1 methanol-to-oil molar ratio, a catalyst quantity of 1 wt.%, and a reaction temperature of 60 °C were the best conditions. It took one hour to produce 93.2% of the biodiesel production under these conditions.

Quality prediction: Machine learning models can be used to predict the quality attributes of biodiesel produced from different waste feedstocks. These models can estimate parameters such as cetane number, viscosity, density, and oxidation stability, enabling producers to ensure compliance with biodiesel standards and regulations. The most popular machine learning technique for predicting quality is an artificial neural network developed by a regression model, which uses input variables such as reaction temperature, reaction time, calcination temperature, pressure, and flow rate and output variables such as fatty acid methyl ester content, viscosity, composition, quantity, cetane number, and density (Xing et al. 2021a). As a function of iodine value and molecular weight, Ramírez-Verduzco et al. (2012) developed a correlation to predict cetane number, viscosity, density, and higher heating value. With the independent variables of iodine value and carbon chain length, Pinzi et al. (2011) provided a mathematical model for low calorific value, kinematic viscosity, flash point, cetane number, and cold filter plugging point. The viscosity, flash point, density, higher heating value, and oxidative stability of biodiesel made from sunflower oil, peanut oil, hydrogenated coconut oil, hydrogenated copra oil, beef tallow, rapeseed oil, and walnut oil were predicted by Mairizal et al. (2020) using multiple linear regressions. The findings suggested that using polyunsaturated/monounsaturated fatty acids balance (PU/MU) as an independent parameter might improve prediction accuracy.

Catalyst selection: Machine learning algorithms can be utilized to identify the most effective catalysts for biodiesel production from specific waste feedstocks. Machine learning models can recommend the best catalysts to achieve high conversion efficiency by analyzing catalyst properties, reaction conditions, and biodiesel yield data. Sukpancharoen et al. (2023) used machine learning techniques to forecast the amount of biodiesel that would be produced from transesterification processes that used three distinct types of catalysts: homogeneous, heterogeneous, and enzyme. The most accurate prediction methods were extreme gradient boosting algorithms, with a coefficient of determination accuracy of over 0.98. The findings showed that, for homogeneous, heterogeneous, and enzyme catalysts, respectively, linoleic acid, behenic acid, and reaction time were the most significant parameters impacting biodiesel yield predictions.

Sustainability assessment: Machine learning techniques can be used to evaluate the environmental impact and sustainability of biodiesel production from waste. Machine learning models can analyze energy consumption, greenhouse gas emissions, and resource utilization data to identify improvement areas and guide sustainable decision-making. In this context, Fangfang et al. (2021) emphasize the potential of waste cooking oil as a valuable feedstock for biodiesel production, highlighting its environmental benefits, economic feasibility, and contribution to waste management using machine learning. The use of artificial neural network modeling provides a reliable tool for simulating and predicting biodiesel production and engine characteristics. The results showed that biodiesel production with 1% catalyst concentration, a 9:1 methanol to waste cooking oil molar ratio, 60 min reaction time, and 500 rpm mixing intensity resulted in reduced waste generation and positive environmental impacts. The artificial neural network model accurately predicted biodiesel yield and engine performance, with overall regression coefficients of 0.98 and 0.99, respectively. This research provides valuable insights into the sustainable production of biodiesel from waste cooking oil, emphasizing the use of artificial neural network modeling for prediction purposes.

Predictive maintenance: Machine learning algorithms can be applied to monitor equipment health and predict

Table 3 Artificial intelligence-based models used for the production of biodiesel from waste feedstock

Waste Feedstock oil	Catalyst	Model	Model input (s)	Model output (s)	Statistical parameter(s)	Reference
Waste cooking oil	Sodium hydroxide (NaOH)	Radial basis function neural network (RBFNN)	Alcohol/oil molar ratio Catalyst weight Reaction temperature Reaction time Mixing intensity	Fatty acid methyl ester (FAME)/ Fatty acid ethyl ester (FAEE)	RBFNN for FAME (RMSE = 2.34, R_C = 0.95, MAE = 1.38) RBFNN for FAEE (RMSE = 3.39, R_C = 0.92, MAE = 1.56)	Najafi et al. (2018)
Waste cooking oil	Sodium hydroxide (NaOH)	Extreme learning machine (ELM)	Alcohol/oil molar ratio Catalyst weight Reaction temperature Residual time	Fatty acid methyl ester (FAME)/ Fatty acid ethyl ester (FAEE)	ELM for FAEE ($R^2{}_C$ = 0.9863, RMSE = 1.7) ELM for FAME ($R^2{}_C$ = 0.9815, RMSE = 1.78)	Faizollahzadeh Ardabili et al. (2018)
Waste cooking oil	Heteropoly acid	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature Residual time	Fatty acid methyl ester (FAME)	MLPNN (R^2 = 0.985)	Talebian-Kiakalaieh et al. (2013)
Waste cooking oil	Sodium hydroxide (NaOH)	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature Reaction time	Fatty acid methyl ester (FAME)	MLPNN (R = 0.9950, $R^2{}_D$ = 0.9950, MAPE = 0.4930, RMSE = 0.735273, MAE = 0.398667, SEP = 0.865754)	Soji-Adekunle et al. (2019)
Waste cooking oil	Sodium hydroxide (NaOH)	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Agitation speed Reaction time	Fatty acid methyl ester (FAME)	MLPNN (R^2 = 0.99, RMSE = 1.97)	Avinash and Murugesan (2018)
Waste cooking palm oil	Sr/ZrO_2	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature Reaction time	Fatty acid methyl ester (FAME)	FAME yield (R^2 = 0.8374), Conversion efficiency (R^2 = 0.8671)	Saeidi et al. (2016)
Waste groundnut oil	Sodium hydroxide (NaOH) and potassium hydroxide (KOH)	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature Reaction time	Fatty acid methyl ester (FAME)	MLPNN (R^2 for NaOH = 0.89396, R^2 for KOH = 0.82921)	Ayoola et al. (2019)
Waste coconut oil	Potassium hydroxide (KOH)	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature	Fatty acid ethyl ester (FAEE)	MLPNN ($R_2{}^D$ = 0.9980, RMSE = 0.68615, SEP = 7.567×10^{-3}, MAE = 0.325, MRPD = 0.3877)	Samuel and Okwu (2019)
Waste olive oil	Potassium hydroxide (KOH)	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction temperature Reaction time	Fatty acid methyl ester (FAME)	Not mentioned	Yuste and Dorado (2006)

Table 3 (continued)

Waste Feedstock oil	Catalyst	Model	Model input (s)	Model output (s)	Statistical parameter(s)	Reference
Schizochytrium algae oil	Sodium-doped nanohydroxyapatite	Multilayer perceptron neural network (MLPNN) with one hidden layer	Alcohol/oil molar ratio Catalyst weight Reaction time	Fatty acid methyl ester (FAME)	MLPNN (R = 0.97365, $R_2^D = 0.9856$)	Kowthaman and Varadappan (2019)

Models such as radial basis function neural network, extreme learning machine, support vector machine with radial basis function kernel, andmultilayer perceptron neural network are applied in this context. These models are fed inputs, including alcohol/oil molar ratio, catalyst weight, reaction temperature, time, mixing intensity, agitation speed, water content, and impurity. The model outputs encompass properties like fatty acid methyl ester, fatty acid ethyl ester, viscosity, turbidity, density, and high heating value. Each model corresponds to specific references detailing waste feedstock-oil and catalyst combinations. RMSE refers to root mean square error, MAE refers to mean absolute error, MAPE refers to mean absolute percentage error, SEP refers to the standard error of prediction, MRPD refers to mean relative percentage deviation, R refers to the Pearson correlation coefficient, R^2 refers to the square of Pearson correlation coefficient, R_C refers to the regression correlation coefficient, $R^2{}_C$ refers to the square of regression correlation coefficient, and $R^2{}_D$ refers to the coefficient of determination

maintenance needs in biodiesel production plants. Machine learning models can anticipate equipment failures, optimize maintenance schedules, and reduce downtime by analyzing sensor data and historical maintenance records. Kanawaday and Sane (2017) emphasized the significance of machine learning in the industrial internet of things (IIoT), particularly in quality management, quality control, cost-effective maintenance, and enhancing productivity to predict possible failures and quality defects in order to improve the overall manufacturing process. The paper also discusses the data collection process from the slitting machine, including the machine details and the system setup using a programmable logic controller (PLC), supervisory control and data acquisition (SCADA), industrial personal computer (IPC), and cloud platforms. In addition, the research concludes that internet of things-based machine learning, coupled with predictive maintenance techniques, can effectively address productivity and maintenance cost limitations. It emphasizes the significance of supervised models for extracting insights from data and using prognostics and forecasting to ensure efficient production processes and minimize maintenance costs and product quality degradation. The paper contributes to the literature on predictive maintenance using internet of things sensor data in industrial settings. The findings highlight the potential of machine learning techniques, specifically auto-regressive integrated moving averages (ARIMA), in improving the overall manufacturing process by predicting failures and enhancing productivity. The research mentioned above discusses the advancement from predictive maintenance to intelligent maintenance using artificial intelligence and the industrial internet of things.

Zheng et al. (2020) evaluated the state of predictive maintenance approaches and proposed an innovative framework called intelligent maintenance. The study reviews the evolution of reliability modeling technology and introduces key framework components, including machine learning algorithms, real-time data collection through wireless smart sensors, big data technologies, and mobile device applications. The paper highlights the importance of addressing challenges such as implementing artificial intelligence and machine learning algorithms for manufacturing time series data, collecting data from remote sources, processing and storing high-frequency data, keeping models up to date, and enabling fast decision-making in the field. The authors also propose a novel probabilistic deep learning reliability modeling approach and demonstrate its application using the turbofan engine degradation dataset. The evolution of reliability technologies is outlined, and the potential of artificial intelligence and the industrial Internet of Things (IoT) for enhancing maintenance practices across different industries is highlighted.

Process scale-up and optimization: Utilize machine learning models to predict the performance of biodiesel production processes at different scales. By extrapolating data from lab-scale experiments and pilot plants, these models can provide insights into process scalability and guide decision-making for large-scale production. Ajala et al. (2023) discussed the development of artificial intelligence techno-economic models for predicting the overall cost–benefit value of large-scale biodiesel production from palm kernel oil. The study aims to provide fundamental investment decisions for potential investors. The article emphasizes the economic viability of large-scale biodiesel production from palm kernel oil and highlights investors' challenges in making informed decisions. By utilizing artificial intelligence models, the study provides a means to predict the cost–benefit value and assists in optimizing the scale-up process for biodiesel production. In the context of scale-up in biodiesel production, this research demonstrates the effectiveness of artificial intelligence techniques in predicting techno-economic parameters. It emphasizes the significance of considering input parameters, particularly catalyst calcination temperature, in the scale-up process. The findings of this study can be valuable for researchers and investors seeking to optimize large-scale biodiesel production and make informed investment decisions.

Challenges

Machine learning and artificial intelligence-based models used for biodiesel predictions from waste face several challenges that need to be addressed:

Ensuring data quality and availability: Obtaining high-quality and comprehensive datasets for training machine learning models can be difficult. The data may contain missing values, outliers, or inaccuracies, which must be addressed through data preprocessing techniques. Additionally, collecting diverse waste sources and covering a wide range of operating conditions may necessitate extensive data collection efforts (Ascher et al. 2022; Mowbray et al. 2021; Wang et al. 2022b).

Handling feature selection and dimensionality: Identifying the most relevant features or variables that influence biodiesel production from waste can be intricate. Waste feedstocks and production parameters may possess numerous dimensions, resulting in high-dimensional feature spaces. It is crucial to select an optimal set of features that significantly contribute to prediction accuracy while reducing dimensionality to enhance model performance (Abdulwahab et al. 2022; Balabin and Smirnov 2011; Cai et al. 2018; Rong et al. 2019).

Dealing with model complexity and interpretability: Advanced machine learning and artificial intelligence techniques like neural networks and ensemble models can offer high prediction accuracy but often lack interpretability (Wang et al. 2022b). Understanding the underlying mechanisms and decision-making processes of complex models can be challenging, especially in the context of biodiesel production from waste. In certain cases, interpretable models may be preferred, emphasizing transparency and explainability (Ascher et al. 2022; Lim et al. 2023; Yang et al. 2023b).

Ensuring generalization and transferability: One of the main challenges for generative models is ensuring the transferability of computationally predicted lead candidates to synthesis and experiment (Hase et al. 2020; Osman et al. 2023b). Thus, it is vital to ensure that machine learning models can generalize well to unseen data and be transferable to different waste feedstocks and operating conditions. Models trained on specific datasets or waste sources may not perform effectively when applied to new, unseen data. Therefore, developing robust models capable of handling variations in waste composition and operating parameters is necessary for practical applications.

Conducting model validation and evaluation: Assessing the performance of machine learning models for biodiesel production prediction requires appropriate validation and evaluation techniques (Mondal et al. 2023). Selecting suitable evaluation metrics and establishing robust validation procedures are essential for reliable and accurate performance assessment. Additionally, model evaluation should account for prediction uncertainties and quantify confidence in the results.

Ensuring scalability and computational efficiency: Implementing machine learning and artificial intelligence models that can handle large volumes of data and provide real-time predictions is crucial for their practical deployment in biodiesel production processes. Ensuring the scalability and computational efficiency of the models is vital to enable efficient prediction and decision-making in real-world scenarios (Cui et al. 2021b).

Addressing ethical considerations: Machine learning and artificial intelligence-based models used in biodiesel production prediction from waste must address ethical considerations (Ahmad et al. 2021; Okolie et al. 2022). This includes addressing privacy concerns related to data collection, storage, and usage. Biases in the data or models need to be identified and mitigated to ensure fair and unbiased predictions. Compliance with regulatory guidelines and ethical standards should be maintained throughout the development and deployment of machine learning-based systems.

In conclusion, machine learning stands out as a potent tool in the realm of converting waste into biodiesel. It utilizes extensive data generated during production to effectively scrutinize and enhance various biodiesel production facets, resulting in heightened efficiency, cost-effectiveness, and sustainability. One pivotal role of machine learning involves identifying and assessing suitable waste materials for biodiesel production. Through analyzing the chemical composition and traits of diverse waste sources, machine learning models enable researchers to pinpoint the most promising materials and refine their conversion into biodiesel. Moreover, machine learning algorithms play a crucial role in optimizing processes by examining large datasets to determine ideal conditions and parameters. By continuously monitoring real-time production data, machine learning can identify inefficiencies, predict potential issues, and propose adjustments to enhance the overall yield and quality of biodiesel. Additionally, machine learning techniques contribute to designing and managing biodiesel production systems. Leveraging historical data and advanced modeling, machine learning aids in optimizing reactors, catalysts, and separation processes, fostering more efficient and sustainable biodiesel production. Ultimately, integrating machine learning into biodiesel production from waste holds significant potential for advancing the field and promoting a more sustainable, eco-friendly energy landscape. Continued research and development in this area is likely to yield further breakthroughs and innovations, making biodiesel a compelling and viable alternative to fossil fuels.

Biodiesel characteristics

Biodiesel is created by combining alkyl esters of long-chain fatty acids derived from various vegetable oils and animal fats. It possesses several key characteristics such as biodegradability, low sulfur content, absence of aromatic compounds, a high flash point, lubricating properties, the ability to mix with petroleum diesel in any ratio, a higher cetane number, and a higher oxygen content (10 to 11 wt.%) compared to petrochemical diesel. The fatty acid esters in biodiesel reflect the fatty acid profile of the raw materials used. The major fatty acids are typically straight-chain molecules with 16 to 18 carbon atoms, although some feedstocks may contain significant amounts of other fatty acids. In addition to esters, the final biodiesel product also contains other compounds that are regulated by quality standards, such as ASTM D6751 (American Society for Testing and Materials), European Standard EN 14214, and country-specific standards (Fonseca et al. 2019; Knothe 2010). However, to enhance the performance of biodiesel, it is necessary to reduce its emissions of nitrogen oxides (NOx), improve its oxidation resistance, enhance its ability to flow in cold temperatures and decrease its kinematic viscosity and density (Fonseca et al. 2019; Sander et al. 2018). These improvements are crucial as they mitigate the environmental impact of biodiesel use, reduce dependence on fossil fuels, and lower greenhouse gas emissions (Hasan and Rahman 2017; Knothe and Razon 2017). Table 4 presents biodiesel specifications and limits depending on standards, as well as its compatibility with diesel.

Transesterification

Transesterification is the most widely utilized method for producing biodiesel at both industrial and laboratory levels. Transesterification implies the use of an organic solvent, often short-chain alcohols, to transform triglycerides and/or free fatty acids (FFAs) into esters. Various fatty acid composition profiles are found in edible and non-edible oils, discarded and recycled greases, animal fats, and edible oil wastes that serve as the sources for these lipids (Andreo-Martínez et al. 2022). The transesterification process includes the reaction of edible or non-edible oil with or without a catalyst. To produce biodiesel, three moles of alcohol react with one mole of oil. After shifting the equilibrium to the right side, for example, product formation, more alcohol is utilized to achieve a high biodiesel yield. In the transesterification reaction, aliphatic alcohol can be used with one replaceable hydrogen atom and 1–8 carbon atoms. Usually, methanol or ethanol are employed as alcohol reactants in producing biodiesel from vegetable oils and animal fats (Kayode and Hart 2019).

Methanol is commonly employed in transesterification processes due to its low cost and availability. In addition, methanol is characterized by its strong polarity, short length, and rapid reaction rate (Andreo-Martínez et al. 2022; Nayab et al. 2022). As an alternative, short-chain alcohols such as isopropanol can be used. Transesterification produces around 10 wt.% glycerol as an extra product. As a result, boosting biodiesel production increases glycerol synthesis, which can subsequently be utilized to produce hydrogen (Kamonsuangkasem et al. 2017). Ethanol is derived from agricultural products and is, to some extent, recyclable and environmentally benign; as a result, it is preferred in the transesterification reaction.

The pretreatment process of waste materials plays a crucial role in the transesterification reaction for biodiesel production. It offers several benefits that contribute to the overall efficiency and quality of the process. There are some key benefits of pretreatment, such as the removal of impurities in waste materials such as water, free fatty acids, and solid particles (Kara et al. 2018; Liu et al. 2021; Suzihaque et al. 2022). Reduction of free fatty acids is useful as the high levels of free fatty acids in the feedstock can negatively impact the transesterification process by consuming the catalyst and forming soaps (Alptekin et al. 2014; Sadaf et al. 2018; Tu et al. 2017). Water removal is important as water present in the feedstock can lead to the formation of emulsions during transesterification, which hinders the separation of biodiesel and glycerol phases (Abusweireh et al. 2022; Kolhe et al. 2017; Sadaf et al. 2018; Suthar et al. 2019). In addition, some solid materials may contain substances that can interfere with

Table 4 Specifications of biodiesel in accordance with standards and its association with diesel characteristics (Ambat et al. 2018; Fonseca et al. 2019)

Properties	Unit	ASTM D6751	EN 14214
Composition of biodiesel	-	C12–C22	C12–C22
Ester's content	% (m/m)	Not available	Greater than 96.5
Density at 15 °C	kg/m^3	Not available	860–900
Viscosity at 40 °C	mm^2/s	1.9–6	3.5–5
Flash point	°C	Greater than or equal to 130	Greater than or equal to 101
Sulfur content	mg/kg	Less than or equal to 50	Less than or equal to 10
Carbon residue	% (m/m)	Less than or equal to 0.05	Less than or equal to 0.3
Cetane number	-	Greater than or equal to 47	Greater than or equal to 51
Sulfated ash	% (m/m)	Less than or equal to 0.02	Less than or equal to 0.02
Water content	% (v/v)	Less than or equal to 0.05	Less than or equal to 0.05
Corrosion	h	3	Not available
Oxidative stability 110 °C	h	Greater than or equal to 3	Greater than or equal to 4
Acid value	mg KOH/g	Less than or equal to 0.5	Less than or equal to 0.5
Iodine value	$(gI_2/100gm)$	Not available	130
Methanol content	% (m/m)	Not available	Less than or equal to 0.02
Monoacylglycerols content	% (m/m)	Not available	Less than or equal to 0.8
Diacylglycerols content	% (m/m)	Not available	Less than or equal to 0.2
Triacylglycerols content	% (m/m)	Not available	Less than or equal to 0.2
Free glycerin	% (m/m)	Less than or equal to 0.2	Less than or equal to 0.02
Total glycerin	% (m/m)	Less than or equal to 0.25	Less than or equal to 0.25
Pour point	°C	− 15 to − 16	Not available
Phosphorus amount	% (m/m)	Less than or equal to 0.001	Less than or equal to 0.0004
Cloud point	°C	− 3 to − 12	Not available

The table presents various parameters that define biodiesel properties, including ester composition, density, viscosity, flash point, sulfur content, carbon residue, cetane number, sulfated ash, water content, corrosion resistance, oxidative stability, acid value, iodine value, methanol content, monoacylglycerols, diacylglycerols, triacylglycerols content, free glycerin, total glycerin, pour point, phosphorus amount, and cloud point. These parameters are crucial for assessing biodiesel quality and compliance with ASTM D6751 (American Society for Testing and Materials) and European Standard EN 14214 standards, which serve as reference guidelines. The properties of biodiesel are influenced by factors such as the composition of fatty acid esters, chain size, and degree of unsaturation. Adjusting the ester composition can lead to biodiesel with improved properties. The flash point, which indicates the boiling point of fuel components, is higher in biodiesel compared to regular diesel. Cloud point, influenced by the amount of saturated fatty acid esters, becomes particularly significant at lower temperatures

or deactivate the catalyst used in the transesterification reaction (Banković-Ilić et al. 2017; Morales et al. 2011).

In biodiesel production, there are two main approaches to transesterification: non-catalytic and catalytic transesterification. In the non-catalytic transesterification method, the use of a catalyst is not necessary to initiate the reaction. The need for product purification is eliminated with this approach. This method can be applied to feedstocks with high water content since the presence of water does not affect the supercritical methanol process. The supercritical procedure typically takes 2–4 min, as it has a faster reaction rate, requiring less time than other technologies.

Additionally, this process can be utilized for various types of raw materials with minimal impurities. The non-catalytic transesterification process generally involves a two-step reaction: first, the feedstock is heated to a high temperature, which causes the triglycerides to melt and become more reactive. Then, an excess of alcohol is added to the heated feedstock, and the mixture is maintained at an elevated temperature for a specified period. The reaction proceeds through heat-induced transesterification, resulting in the formation of biodiesel and glycerol. Non-catalytic transesterification has some advantages, such as simplified process setup and lower catalyst costs. However, the non-catalytic transesterification method requires high reaction pressure and temperature. This can lead to the breakdown of unsaturated fatty acids, negatively impacting the fuel's fluidity at lower temperatures. Furthermore, using supercritical methanol in non-catalytic transesterification is not economically feasible and consumes significant energy. In addition, it usually requires higher energy input and longer reaction times compared to catalytic transesterification. Therefore, it is less commonly used on an industrial scale, but it can be suitable for smaller-scale or research applications. To address these disadvantages, some scientists have introduced a small amount of co-solvent or solid catalysts like calcium oxide and supercritical methanol to produce more efficient biodiesel (Marchetti 2012; Nayab et al. 2022).

In the realm of utilization, non-catalytic transesterification is employed in converting waste into biodiesel. Jung et al. (2022) conducted a study where they employed non-catalytic transesterification to convert food waste into biodiesel. They utilized black soldier fly larvae (BSFL) as a means to convert the nutrients in food waste into lipids, which were subsequently transformed into biodiesel. The non-catalytic transesterification process achieved a yield of 94.1 wt.% when performed for 1 min at 390 °C in the presence of a porous material (SiO_2). Interestingly, the non-catalytic reaction was successful in directly converting BSFL without the need for lipid extraction. The highest biodiesel yield obtained from the direct conversion of BSFL was 94.7 wt.% when the reaction was conducted at 390 °C for 1 min. The properties of the biodiesel derived from BSFL were measured in the study, revealing a density of 880 kg/m^3, viscosity of 4 mm^2/s, flash point of 131 °C, and acid value of 0.12 mg KOH/g. These findings confirm that non-catalytic transesterification holds promise as a viable technical platform for converting food waste into biodiesel. Consequently, considering food waste as a resource for biodiesel production is a plausible approach based on the results obtained.

The second approche of transesterification process is catalytic transesterification. Catalytic transesterification, due to the presence of a catalyst, is the most prevalent method for producing biodiesel, where glycerol and ester are generated when triglyceride combines with alcohol in the presence of a catalyst, which facilitates the breaking of ester bonds in the triglycerides. Nature-connected fatty acids define the properties of triglyceride or fat/oil, implying that the nature of fatty acids directly impacts the behavior or properties of biodiesel (Shaah et al. 2022). The primary function of a catalyst in transesterification is to increase the reaction rate and promote the formation of biodiesel. It achieves this by lowering the activation energy required for the chemical reaction to occur. Thus, the catalyst provides an alternative reaction pathway that reduces the energy barrier, enabling the esterification or transesterification reactions to proceed more rapidly (Mofijur et al. 2021). In catalytic transesterification, the catalyst can be either homogeneous or heterogeneous. In homogeneous catalysis, the catalyst is in the same phase as the reactants. This means that the catalyst is dissolved in the reaction mixture. Alkaline catalysts, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), are commonly used in homogeneous catalytic transesterification. They provide high reaction rates and are effective for a wide range of feedstocks. However, they require careful handling due to their corrosive nature and can lead to soap formation, which requires additional purification steps (Naeem et al. 2021; Sajjad et al. 2022; Vishal et al. 2020).

Furthermore, acid catalysts, such as sulfuric acid (H_2SO_4) or hydrochloric acid (HCl), can also be used in transesterification reactions, particularly for low-quality feedstocks with high free fatty acid content. Acid catalysts work by converting the free fatty acids present in the feedstock into esters, which can then undergo transesterification with alcohol. Acid catalysts are typically used in homogeneous catalytic transesterification, similar to alkaline catalysts. Acid catalysts offer advantages such as lower sensitivity to water content in the feedstock and the ability to handle feedstocks with higher acid values. However, they have drawbacks such as corrosion concerns, the need for additional neutralization steps, and lower reaction rates compared to alkaline catalysts (Ejeromedoghene 2021; Gebremariam and Marchetti 2021). In heterogeneous catalysis, the catalyst is in a different phase from the reactants (Lourinho and Brito 2015). Typically, solid catalysts, such as metal oxides such as calcium oxide and magnesium oxide (Afsharizadeh and Mohsennia 2019; Sulaiman et al. 2021) or supported catalysts, such as solid acids or bases on inert support (de Oliveira et al. 2022; Zhang et al. 2023), are used. Heterogeneous catalytic transesterification offers advantages such as easier catalyst separation, reduced soap formation, and potential reusability of the catalyst. However, it may have lower reaction rates compared to homogeneous catalysis.

Transesterification reactions are frequently conducted in reactors. The chemical nature of the feedstock and product, as well as the physical parameters of the operation, affect how each reactor operates. The optimum operating conditions and the amount of output are the major factors in reactor selection (Raheem et al. 2020). Spinning disc reactors (Chaudhuri et al. 2022; Qiu et al. 2012), spinning tube reactors (Chanthon et al. 2021; Lodha et al. 2012), continuously stirred tank reactors (Castillo Gonzalez et al. 2020; Kouzu et al. 2018), oscillatory flow reactors (García-Martín et al. 2018; Niyas and Shaija 2023), microwave reactors (Hsiao et al. 2021; Lawan et al. 2020), micro channel reactors (Santana et al. 2017; Sootchiewcharn et al. 2015), fixed bed reactor (Budžaki et al. 2018; Hama et al. 2013), simultaneous reaction-separation reactors (Fayyazi et al. 2018), and membrane reactors (Alsaiari et al. 2023; Luo et al. 2023) are examples of different types of reactors used in the transesterification process. Several factors, such as reaction temperature, reaction time, alcohol-to-oil ratio, type and quantity of catalyst, and feedstock composition, affect the transesterification reaction (Banerjee et al. 2018; Patchimpet et al. 2020). Table 5 lists the transesterification reaction conditions of different waste feedstocks for biodiesel production.

Table 5 Transesterification reaction conditions of different waste feedstocks for biodiesel production

Waste feedstock oil	Catalyst	Reaction temperature (°C)	Alcohol-to-oil ratio	Time (min)	Fatty acid methyl ester (FAME) yield (%)	References
Waste cooking oil	EFB activated carbon	70	12:1	120	97.1	Abdullah et al. (2022)
Waste cooking oil	NaOH	45	12:1	195	82	Sivarethinamohan et al. (2022)
Waste cooking oil	zeolite supported CaO	69.1	9.7:1	238.8	93.7	Yusuff et al. (2022)
Waste cooking oil	CaO/Fe_2O_3	65	11:1	Not available	98.7	Echaroj et al. (2023)
Waste cooking oil	KNO_3/Oil shale ash	65	45:1	120	100	Al-Hamamre et al. (2023)
Waste cooking oil	CaO/Al_2O_3	45	7:1	180	95	Abu-Ghazala et al. (2023)
Waste cooking oil	Biochar/CaO/K_2CO_3	65	18: 1	200	98.83	Foroutan et al. (2021)
Waste Chicken Fat	CaO	60	13:1	60	96	Saleem et al. (2022)
Waste Chicken Fat	TPC-SO_3H	70	15:1	120	Greater than 90	Maafa (2022)
Waste Chicken Fat	SrO/SiO_2	65	12:1	60	98.9	Riaz et al. (2023)
Goat fat	MgO	70	12:1	180	93.12	Rasouli and Esmaeili (2019)
Waste beef tallow	(Ce-CaO-SiO_2)	70	11	100	95.29	Al-Muhtaseb et al. (2022)
Waste animal fats (veal, beef, pork, goose, chicken)	NaOH	60	6:1	1440	Not available	Sander et al. (2018)
Waste vegetable oil	KOH	65	6:1	60	96.15	Refaat et al. (2008)
Waste vegetable oil (waste sunflower oil)	CaO/Al_2O_3	65	9:1	240	80	Elias et al. (2020)
Waste vegetable oil (waste palm oil)	CaO/Al_2O_3	65	9:1	240	60	Elias et al. (2020)
Waste fish oil	Lipase biocatalyst	35	3:1	1440	75.3	Ching-Velasquez et al. (2020)
Waste fish oil	KOH	60	9:1	60	99.1	Kara et al. (2018)
Waste fish oil	CaO	57	25:1	107	86.5	Karkal and Kudre (2023)
Microalgae	CaO	80	9:0.6	240	Not available	Davoodbasha et al. (2021)
Microalgae	$Ca[O(CH_3)]_2$	80	30:1	180	99	Teo et al. (2016)
Microalgae	Mn-ZnO capped with PEG	60	15:1	240	87.5	Vinoth Arul Raj et al. (2019)
Microalgae	Si/ZnO	55	9:1	50	97.3	Kalavathy and Baskar (2019)

The table showcases the transesterification reaction conditions employed for biodiesel production, encompassing different waste feedstocks and catalysts. The table presents crucial details regarding the waste feedstock type, catalyst used, reaction temperature, alcohol-to-oil ratio, reaction time, and the resulting yield of fatty acid methyl ester (FAME). The table provides a comprehensive compilation of optimization approaches adopted by various studies, highlighting the diverse strategies employed to convert specific waste feedstocks into biodiesel. This compilation serves as a valuable resource for researchers and practitioners aiming to explore and enhance biodiesel production from a wide range of waste sources. EFB refers to empty fruit bunch, TPC refers to tire polymer char, and PEG refers to polyethylene glycol

Waste materials for biodiesel production

The global demand for renewable biofuels is steadily increasing as a response to the imperative need to replace fossil fuels in both transportation and power generation. However, the widespread commercial implementation and operation of large-scale biofuel production facilities face numerous challenges. To secure future energy needs and decrease the world's dependence on fossil fuels in critical sectors like infrastructure and industry, it is imperative to drive technological advancements aimed at enhancing the efficiency of biofuel production. Consequently, there is an urgent need for swift progress in sustainable biofuel production to align with the surging global energy demands. The world is grappling with persistent waste management issues that necessitate substantial land and water resources for proper handling and processing. An attractive and forward-thinking solution lies in the transformation of waste materials into energy resources (Stephen and Periyasamy 2018). This approach not only addresses the waste management challenge but also contributes to a more sustainable and eco-friendly energy landscape.

Biodiesel can be a practical and sustainable alternative fuel. However, it faces several challenges, including its comparatively higher production expenses, lower energy content in comparison to fossil diesel, and the emission of nitrogen oxide pollutants during combustion. The elevated production cost primarily impedes its widespread adoption. To address this, three potential approaches can be pursued: enhancing production technology for increased efficiency and yield, reducing capital expenditures, and lowering raw material expenses, with a particular focus on diminishing feedstock costs, which constitute the most significant component (Gebremariam and Marchetti 2018). To reduce production costs, waste materials can be harnessed as alternative feedstocks, and innovative methods can be employed to convert waste into viable feedstock sources.

Additionally, cost-effective catalysts derived from waste materials can be integrated into the biodiesel production process. Researchers are actively exploring and identifying potential waste materials for integration into biodiesel production. Waste-derived feedstocks such as discarded cooking oil and animal fats are gaining popularity, and promising feedstock sources like microalgae and oleaginous fungi can be cultivated utilizing waste streams and materials. Using used cooking oil as a raw material can also reduce the need for its disposal. Additionally, making biodiesel from waste cooking oils helps minimize waste management costs by utilizing more affordable non-edible vegetable oils or waste cooking oils (Topare et al. 2023). Furthermore, various waste materials, including animal bones, eggshells, and plant residues, have been under investigation for synthesizing catalysts used in the transesterification process (Alam et al. 2022). These strategies not only yield economic advantages but also offer environmental benefits by efficiently utilizing and managing waste resources.

Waste cooking oil

The global demand for vegetable oils and fats for edible purposes has steadily increased over the past decade, with an estimated 25% increase in worldwide consumption expected to reach 178 million tons in 2025 (OECD 2022). In Europe, about 11.1 million tons of vegetable oils, with an average of 15 kg per capita per year, were consumed for edible purposes in 2013, with significantly higher consumption rates in the Mediterranean area, particularly in Spain, Italy, and Greece. About 20% of these oils are disposed of after the cooking process, resulting in waste cooking oil. Waste cooking oil is recovered from households, restaurants, hotels, and food processing facilities after deep-frying and other meal preparation processes. European Union countries generate 0.7 to 1 million tons of waste cooking oil annually, while the United Kingdom and Canada produce 0.2 and 0.135 million tons of waste cooking oil annually, respectively. China and Japan generate an estimated 4.5 and 0.6 million tons of waste cooking oil annually, respectively (Hamze et al. 2015).

Waste cooking oil is unsuitable for culinary use and harmful to the environment due to physical and chemical changes that occur during frying, including oxidative and hydrolytic reactions. The dissolved oxygen reacts with unsaturated acylglycerols, producing toxic oxidation products that increase the risk of cancer and cardiovascular disease. Repeated frying also results in oil acidification, which is a health and food safety hazard. Due to these issues and growing public health awareness, oil reuse in the food industry and households is limited (Hosseinzadeh-Bandbafha et al. 2022). In addition, the increased production of used cooking oil is causing severe disposal problems, including water treatment issues such as sewer diameter reduction and blockages in wastewater plant infrastructure (FAO 2013; Lombardi et al. 2018). A promising approach is utilizing waste cooking oil as biodiesel feedstock, which can address issues such as water contamination and drainage system blockages that require additional cleaning (Singh et al. 2021). Therefore, biodiesel production from waste oils addresses environmental pollution and improves the economics of high-cost biodiesel production (Farag et al. 2011; Hamze et al. 2015).

Biodiesel produced from waste cooking oil is biodegradable and non-toxic, with minimal or no sulfur content, and can be used in compression ignition (CI) engines with minor modifications. As compression ignition engines are not developed solely for biodiesel fuel use, the biodiesel analysis is incomplete until it is tested in compression ignition engines (Elkelawy et al. 2022; Singh et al. 2021). A comparison of properties between biodiesel from waste cooking oil and commercial diesel fuel is listed in Table 6.

The transesterification process of waste cooking oil for biodiesel production typically involves several steps, such as the pre-treatment process, which includes filtering the oil to remove solid particles and heating it to remove moisture; the acid esterification process, which may be a necessary step to reduce the free fatty acid content and improves the overall transesterification process, and transesterification process which involves the reaction of the pre-treated waste cooking oil with an alcohol, usually methanol, in the presence of a catalyst, as illustrated in Fig. 4.

Biodiesel production from waste cooking oil offers a multifaceted solution encompassing economic, environmental, and waste management benefits. It also plays a crucial role in cost-effective waste management by partially substituting imports of petrochemical oil (Degfie et al. 2019). According to the Japan Oilseed Processors Association (JOPA), global biodiesel production in 2019 reached 4.48×10^7 tons, with waste cooking oil constituting approximately 10% of the total production (Chen et al. 2021a). Research on waste

Table 6 Comparison of physical, chemical, and performance properties of biodiesel from waste cooking oil and commercial diesel fuel (Demirbas 2009; Yaakob et al. 2013)

Fuel properties	Unit	Biodiesel from waste cooking oil	Commercial diesel fuel
Kinematic viscosity (40 °C)	mm^2/s	5.3	1.9–4.1
Density	kg/L	0.897	0.075–0.84
Pour point	°C	− 11.15	− 19.15 – (− 13.15)
Flash point	°C	195.85	66.85–84.85
Free fatty acid	mgKOH/g	0.1	Not available
Cetane number	-	54	40–46
Carbon residue	%	0.33	0.35–0.4
Ash content	%	0.004	0.008–0.01
Sulfur content	%	0.06	0.35–0.55
Water content	%	0.04	0.02–0.05
Calorific value	MJ/kg	42.65	45.62–46.48

The table provides a comprehensive comparison of various properties between biodiesel derived from waste cooking oil and commercial diesel fuel. The table highlights important fuel properties such as kinematic viscosity, density, pour point, flash point, free fatty acid content, cetane number, carbon residue percentage, ash content percentage, sulfur content percentage, water content percentage, and calorific value. Biodiesel from waste cooking oil exhibits varying values for each parameter, including higher kinematic viscosity, density, pour point, flash point, and free fatty acid content compared to commercial diesel fuel. However, it demonstrates a higher cetane number and lower sulfur content. This comparison provides valuable insights into the physical, chemical, and performance properties of biodiesel from waste cooking oil in relation to commercial diesel fuel, highlighting the potential benefits and considerations for its use as an alternative fuel source

cooking oil-based biodiesel production is an economic field that helps address the global challenge of insufficient energy resources by reducing greenhouse gas emissions, promoting sustainable economic growth, and addressing food safety issues associated with the illegal reuse of waste cooking oil (Chen et al. 2021a; Sharma et al. 2019b). Generally, the advantages and challenges of using waste cooking oil for biodiesel production are listed in Table 7.

Waste animal fat

Globally, the meat and poultry industries are thriving, driven by an increasing population and the demand for food. The annual production of meat and poultry products has reached significant levels, such as 43.42 million tons in the United States of America, 38 million tons in Latin America and the Caribbean, 30 million tons in the European Union, 598 million tons in Australia, 11.1 million tons in Sub-Saharan Africa, 84.89 million tons in China, and 1,323.5 million heads in India. Alongside edible products, these industries generate substantial amounts of animal by-products. Inedible materials account for an estimated 40–60% of the livestock, resulting in the annual disposal of around 27.8 million tons of slaughterhouse materials in North America. Similarly, in the European Union, approximately 29.41% of the 17 million tons of slaughterhouse by-products generated yearly consist of inedible materials. These inedible livestock wastes are commonly used as raw materials in various industries, including tanning, textiles, detergents, fertilizers, and biofuels (Binhweel et al. 2022; Shirzad et al. 2019; Toldrá-Reig et al. 2020a).

Recently, livestock fat from mutton, beef, and chicken has attracted the attention of researchers as a potentially sustainable and cost-effective feedstock. Currently, there is a limited market demand for animal fat, and it is primarily utilized as raw material in the cosmetics and soap industries. Generally, waste animal fats are obtained from discarded fleshing wastes in leather tanneries and fat waste in slaughterhouses and meat processing industries. Although they are unsuitable for consumption, they are rich in triglyceride content, making them an ideal option for biodiesel production (Jambulingam et al. 2019). The use of waste animal fats as an alternative feedstock can address the disposal issue while providing a low-cost source for the biodiesel industry (Andreo-Martínez et al. 2022; Habib et al. 2020). This cost-effective feedstock not only helps mitigate environmental pollution but also enhances the features of biodiesel by increasing the cetane number and improving oxidative stability (Andreo-Martínez et al. 2022). Table 8 summarizes the properties of waste animal fats biodiesel and normal diesel. These waste fats are also highly favored as promising feedstock due to their high energy density. The biodiesel production from waste animal fats using the transesterification process is presented in Fig. 5.

In recent years, numerous studies have focused on utilizing waste materials and pursuing a fully circular economy. This has increased interest in adopting waste animal fats biodiesel as an alternative fuel for compression ignition (CI) engines (Jiaqiang et al. 2017; Ojha et al. 2020; Ubando et al. 2020). The cost of biodiesel derived from waste animal fat depends on various factors, including the cost of the feedstock, the level of free fatty acids, the required pretreatment, the catalyst type, operational maintenance, and purification methods for biodiesel (Rezania et al. 2019). A higher cetane number indicates better ignition quality. Biodiesel produced from animal fats typically has a cetane number above 50, which is higher than that of biodiesel produced from vegetable oils. This is due to the higher percentage of saturated fats (over 40%), lower carbon content, and higher oxygen content than conventional diesel. The acid value is related to the concentration of free fatty acids, which, at high levels, can lead to fuel supply system corrosion in the engine (Alptekin and Canakci 2011; Atabani et al. 2012; Cernat et al. 2019).

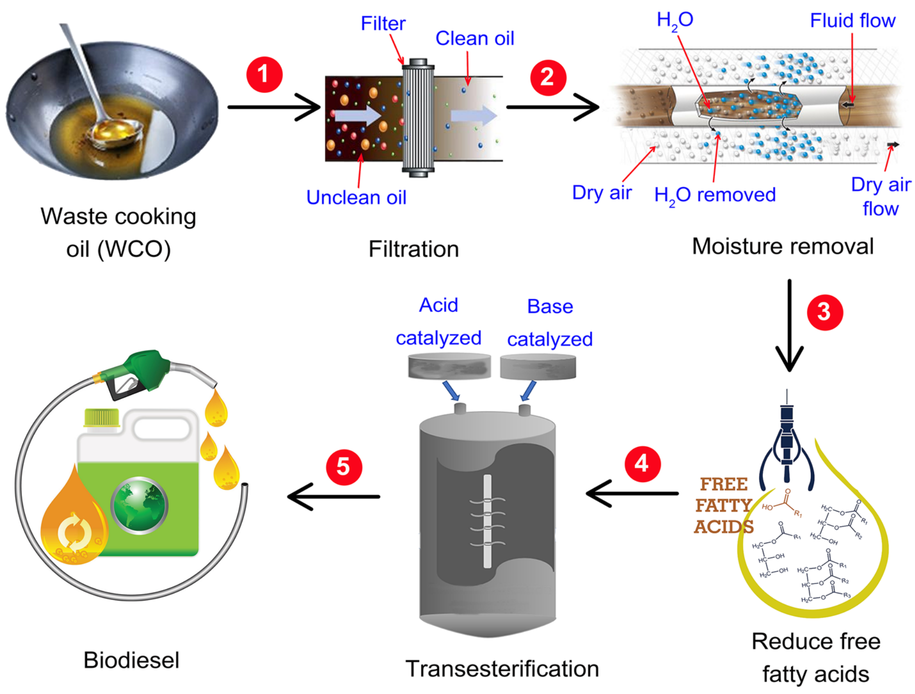

Fig. 4 Biodiesel production from waste cooking oil using transesterification process. The figure demonstrates the multi-step process of producing biodiesel from waste cooking oil through transesterification. Initially, the oil undergoes filtration to eliminate impurities and particulates. Following this, a moisture removal step reduces the water content in the oil to prevent unwanted reactions during transesterification. Subsequently, the oil is subjected to a process that reduces free fatty acids, ensuring better reaction efficiency. Transesterification takes place by introducing a base or acid catalyst, such as sodium hydroxide or sulfuric acid, respectively, in a reactor under controlled temperature and time conditions. This chemical conversion process turns the triglycerides in the oil into biodiesel and glycerol as a byproduct. WCO refers to waste cooking oil

Overall, the advantages and limitations of using waste animal fats for biodiesel production are listed in Table 9.

Waste vegetable oil

The term "waste vegetable oil" refers to vegetable oil that has been used in food production and is no longer suitable for its original purpose. Waste vegetable oil can come from various sources, including households, commercial establishments, and industrial settings. The United States Environmental Protection Agency reports that restaurants produce over 1,000,000 m^3 of waste vegetable oil annually. This feedstock is preferred over virgin oils due to its sustainability (Baroutian et al. 2013), economic viability, waste management improvements, and higher net energy ratio (Lee et al. 2014; Outili et al. 2020). Waste vegetable oil, typically generated by frying, contains compounds like monoglycerides, diglycerides, triglycerides, free fatty acids, and aldehydes (Baroutian et al. 2013; Ganesan et al. 2009).

Proper management of waste vegetable oil is crucial because its disposal can pose problems. When wrongly disposed of down kitchen sinks, waste vegetable oil can solidify and cause blockages in sewer pipes, leading to issues such as corrosion of metal and concrete elements in sewage systems and affecting wastewater treatment plants. This, in turn, increases the cost of treating effluents and maintaining waterways (Refaat 2010). Additionally, fresh vegetable oil-derived biofuels have been considered expensive and less cost-effective than petroleum-based diesel. As a result, waste vegetable oil presents a promising alternative to unused vegetable oils for biodiesel production. Additionally, utilizing waste vegetable oil instead of fresh vegetable oils is cost-effective and helps reduce environmental issues related to waste oil disposal (Yilmaz and Morton 2011). Vegetable oil is also seen as a crucial solution in combating global warming and stabilizing the climate by reducing carbon dioxide emissions.

According to previous investigations on waste vegetable oil biodiesel, Singh et al. (2017) investigated the physicochemical characteristics of waste vegetable oil biodiesel and found cetane number of 48, calorific value of 36.2 MJ/kg, density of 0.86 g/cm^3, viscosity of 3.78 mm^2/s, flash point 135 °C, fire point 149 °C, cloud point 5 °C, and acid value of 2.82 mgKOH/g. Sharon et al. (2012) conducted a study on the physicochemical properties of vegetable fried biodiesel and observed a calorific value of 42.58 MJ/kg, viscosity of 5.11 mm^2/s, cetane number of 61.28, density of 876.1 g/cm^3, flash point of 161 °C, pour point of 7 °C,

Table 7 Advantages and challenges of using waste cooking oil as a feedstock for biodiesel production

Parameter	Waste cooking oil as a feedstock for biodiesel production	References
Advantages	Energy security: Utilizing waste cooking oil for biodiesel production helps diversify energy sources and reduces dependence on imported fossil fuels. It promotes energy security by utilizing locally available resources Waste management: Utilizing waste cooking oil for biodiesel production offers an environmentally friendly solution for its disposal. Instead of discarding the used cooking oil, which can be harmful if improperly disposed of, it can be converted into a valuable resource Renewable and sustainable: Waste cooking oil is a renewable feedstock that can be continuously generated from cooking processes. By converting it into biodiesel, a renewable and sustainable fuel source, the dependence on finite fossil fuels can be reduced Cost-effectiveness: Waste cooking oil is readily available as a by-product from various food processing industries and restaurants. Its use as a feedstock for biodiesel production can help reduce the cost of raw materials, making biodiesel production more economically viable. The cost of acquiring waste cooking oil is approximately 2.5–3.5 times less expensive than using edible vegetable oils, making biodiesel produced from recycled oils a potentially cost-effective alternative that can reduce the environmental burden of waste cooking oil disposal Lower carbon footprint: Biodiesel produced from waste cooking oil generally has a lower carbon footprint than traditional diesel fuel. It emits fewer greenhouse gases during combustion, contributing to reduced air pollution and mitigating climate change Job creation and economic benefits: Biodiesel production from waste cooking oil can stimulate local economies by creating job opportunities in the collection, processing, and production stages. It can contribute to the growth of a sustainable bioenergy industry Compatibility with existing infrastructure: Biodiesel derived from waste cooking oil can be used in existing diesel engines and infrastructure without significant modifications. This compatibility allows for a seamless transition to biodiesel as a renewable fuel option	Aderibigbe et al. (2023), Goh et al. (2020), Gómez-Trejo-López et al. (2022), Hosseinzadeh-Bandbafha et al. (2022), Rehan et al. (2018)

Table 7 (continued)

Parameter	Waste cooking oil as a feedstock for biodiesel production	References
Challenges	Quality and consistency: Waste cooking oil can vary in quality and composition, depending on its source and the cooking processes it has undergone. Contaminants such as water, food particles, and impurities may be present in the oil, which can affect the efficiency of biodiesel production and require additional pre-treatment steps Contaminant removal: Before converting waste cooking oil into biodiesel, it is necessary to remove impurities and contaminants through processes such as filtration and purification. These additional steps increase the complexity and cost of biodiesel production Limited availability: While waste cooking oil is generated in significant quantities in food processing industries and restaurants, its collection and availability can be geographically limited. Establishing a consistent and reliable supply chain for waste cooking oil can be a logistical challenge, especially in areas with lower food consumption or limited collection infrastructure Competition with other applications: Waste cooking oil has various potential applications, such as animal feed or industrial processes. The demand for waste cooking oil in these alternative sectors can create competition, affecting its availability and increasing its market price for biodiesel production Storage and handling: Waste cooking oil requires proper storage and handling to prevent degradation and contamination. It is prone to spoilage, rancidity, and microbial growth, which can impact the quality and suitability of the oil for biodiesel production Feedstock variability: The composition and characteristics of waste cooking oil can vary depending on factors such as the type of cooking oil used, food preparation methods, and storage conditions. This variability can pose challenges in achieving consistent biodiesel quality and performance Regulations and quality standards: Biodiesel production from waste cooking oil must meet regulatory requirements and quality standards to ensure its compatibility with engines, reduce emissions, and maintain overall fuel quality. Compliance with these standards can add complexity and additional costs to the production process The price of waste cooking oil -based biodiesel varies based on regional, geographical, and agricultural conditions, as well as the quality and availability of raw materials collection and distribution facilities throughout the year	Chen et al. (2021a), Foo et al. (2021), Foo et al. (2022), Janbarari and Ahmadian Behrooz (2020), Manikandan et al. (2023), Tropecêlo et al. (2016)

The advantages of using waste cooking oil as a feedstock for biodiesel production encompass diverse aspects. These include enhancing energy security through source diversification, addressing waste management concerns by offering an eco-friendly disposal solution, and utilizing a renewable and sustainable resource. Moreover, this approach facilitates cost-effectiveness due to the material's availability and affordability while also reducing carbon emissions to combat air pollution and providing economic benefits by creating employment opportunities. Additionally, it ensures compatibility with existing infrastructure. On the other hand, challenges in this process involve various factors. These include ensuring waste cooking oil's quality and consistency, implementing additional pre-treatment steps for contaminant removal, addressing limited availability, establishing a reliable supply chain, and managing competition with alternative applications. Other challenges include adhering to proper storage and handling requirements, accounting for feedstock variability impacting biodiesel quality, complying with regulations and quality standards, and dealing with price variations in waste cooking oil-based biodiesel

and cloud point of 13 °C. Al-Widyan et al. (2002) found a calorific value of 39.3 MJ/kg and a flash point of 109 °C. Similarly, Wang et al. (2017) reported a density of 885 kg/m^3, kinematic viscosity of 4.5 mm^2/s, and calorific value of 38 kJ/g.

Local governments are collecting used melt-out oils from domestic consumption and converting them into biodiesel fuel for public transport as an alternative to fossil diesel fuel (Brito et al. 2007; Lee et al. 2011). Modern jet engines have demonstrated satisfactory performance when fueled by vegetable oil-derived fuels rather than petroleum-based fuels. It is worth noting that waste cooking oil and waste vegetable oil are used as feedstocks for biodiesel production. However, there are distinctions between them. Waste cooking oil encompasses oils used for cooking, including animal fats and vegetable oils, while waste vegetable oil specifically refers to discarded vegetable oils used in cooking. Waste cooking oil may contain a mix of different oil types and is more likely to have higher impurities due to its commercial use, whereas waste vegetable oil consists solely

Table 8 Comparison of properties between biodiesel from waste animal fats and normal diesel (Srinivasan et al. 2020)

Fuel properties	Standard	Unit	Biodiesel from waste animal fats	Normal diesel
Chemical formula	–	–	$C_{19}H_{38}O_2$	$C_{16}H_{28}$
Density	ASTM D1298	kg/m^3	887	830
Kinematic viscosity	ASTM D445	mm^2/s	4.82	3.6
Specific gravity	ASTM D1298	–	0.887	0.83
Flash point	ASTM D93-16	°C	149	90
Pour point	ASTM D7346-15	°C	−3.27	−13
Fire point	ASTM D93-16	°C	162	100
Cloud point	ASTM D2500	°C	2.16	0
Cetane number	ASTM D613	–	66	50
Calorific value	ASTM D240	MJ/kg	37.3	42.5
Iodine value	ASTM D5554	(gI_2/100 gm)	32.27	Not available
Saponification value	ASTM D5558	(mgKOH/gm)	183.27	Not available
Carbon content	ASTM D5291	(wt.%)	76.45	85.16
Oxygen content	ASTM D5291	(wt.%)	10.72	Not available
Sulfur content	ASTM D5291	(wt.%)	Not available	0.152
Hydrogen content	ASTM D5291	(wt.%)	12.81	14.26

The table presents a comprehensive comparison between biodiesel derived from waste animal fats and conventional diesel fuel across various properties. Biodiesel derived from waste animal fats exhibits specific characteristics in contrast to normal diesel. Differences in density, kinematic viscosity, specific gravity, flash point, pour point, fire point, cloud point, cetane number, calorific value, iodine value, saponification value, carbon content, oxygen content, sulfur content, and hydrogen content are outlined based on standards such as ASTM D1298, ASTM D445, ASTM D93-16, ASTM D7346-15, ASTM D2500, ASTM D613, ASTM D240, ASTM D5554, ASTM D5558, and ASTM D5291. These comparative metrics shed light on the varying properties of biodiesel from waste animal fats when compared to regular diesel, illustrating potential differences in their performance and suitability for different applications. ASTM refers to the American Society for Testing and Materials

of vegetable oils used for cooking and may have fewer contaminants. Waste cooking oil is generally more readily available in larger quantities, primarily sourced from food establishments, while waste vegetable oil is primarily obtained from household cooking activities and may not be as easily accessible in significant amounts. Despite these differences, both waste cooking oil and waste vegetable oil undergo similar processing steps for biodiesel production, with potential additional pre-treatment steps for waste cooking oil to remove impurities before transesterification. Biodiesel fuel production from waste vegetable oil has several advantages and limitations, as illustrated in Table 10.

Algae

Algae primarily rely on photosynthesis to survive and are photoautotrophic. Through photosynthesis, algae utilize solar energy to combine water with carbon dioxide, resulting in the creation of algal biomass (Hidalgo et al. 2013). The high biomass and photosynthetic efficiency of microalgae contribute to their rapid growth rates and ability to mitigate carbon dioxide levels (Moshood et al. 2021). Algae are regarded as the fastest-growing aquatic plants globally, and their capacity to produce energy-rich compounds has led to their significant importance. Moreover, the energy consumed during algae processing is lower than the energy they produce, making algae an attractive option for biofuel production. These factors, combined with favorable species composition, contribute to the increased production of biofuels (Thanigaivel et al. 2022). Biofuel from algae, especially microalgae, is considered third-generation biofuel and plays a crucial role in sustainable energy development. In this context, the global market for algal biofuel was valued at 5.02 billion USD in 2020, with an anticipated growth rate of 8.75% to reach 9.03 billion USD by 2027 (Sathya et al. 2023). By 2030, the algal-based biofuel industry is expected to account for approximately 75% of the biofuel market (Ali et al. 2022). Microalgae's appeal lies in their ability to thrive without the need for arable land, their minimal water requirements, efficient absorption of carbon dioxide and release of oxygen, adaptability to aquatic environments, year-round production unaffected by seasonal limitations, non-competition with food resources, resilience to varying conditions, rapid biomass generation, and high oil content (Alishah Aratboni et al. 2019; Ravanipour et al. 2021). However, freshwater microalgae species require substantial freshwater, resulting in a significant water footprint. Therefore, innovative cultivation methods are required to achieve increased biofuel production from different algal strains, focusing on utilizing domestic, industrial, and agricultural wastewater for algal growth. This strategy promotes both wastewater remediation and biofuel production, creating a multifaceted and environmentally friendly approach (Jeyakumar et al. 2022; Sathya et al. 2023; Tiwari et al. 2019).

Microalgae present an enticing option for biodiesel production due to their remarkable attributes. They consist primarily of carbohydrates, proteins, and lipids, with triglycerides being the predominant type of oil for biodiesel production. In addition, Vignesh et al. (2020) reported that biodiesel derived from microalgae is considered a promising substitute for traditional biofuels, offering cost-effectiveness, pollution reduction, and environmental friendliness. These tiny aquatic organisms boast a short growth cycle, typically spanning 2–6 days, and offer high lipid yields, rendering them exceptionally well-suited candidates (Adewuyi 2022). Additionally, microalgae exhibit an exceptional oil content, ranging from 30 to 70% of their dry weight, surpassing that of traditional crops utilized in biofuel production.

Furthermore, their oil production potential is remarkable, with yields reaching up to an impressive 136,900 L of oil per hectare per year, and their land footprint is incredibly minimal, necessitating only 0.1 m^3 for every liter of biodiesel produced (Nishshanka et al. 2022). In fact, microalgae are capable of producing up to 250 times more oil per acre than soybeans and 7–31 times more oil than palm oil, making them the most productive raw materials for biodiesel (Christenson and Sims 2011; Park et al. 2011). Numerous microalgae species, including *Chlorella Vulgaris*, *Botryococcus braunii*, *Chlorella S4*, and *Nannochloropsis gaditana*, have undergone genetic sequencing and exhibit significant promise for biofuel production (Baroukh et al. 2015; Olia et al. 2019). The cultivation of microalgae holds immense potential, with approximately 50,000 known species, of which 30,000 have been identified. Macroalgae, including brown algae, green seaweed, and red algae, are also used for this purpose.

In order to increase the likelihood of using microalgae-based biodiesel production (Makareviciene et al. 2013), it is crucial to identify microalgal species that possess suitable lipid compositions. In this regard, the biodiesel derived from *Desmodesmus sp.*(I-AU1) exhibited favorable physicochemical properties, including low density (880 kg/m^3), low kinematic viscosity (2.81 mm^2/s), cetane number of 43.47, iodine value of 120.4 gI_2/100 gm fat, and higher calorific value of 37.73 MJ/kg, as listed in Table 11. When compared to the established standards, the *Desmodesmus sp.*(I-AU1) biodiesel demonstrated desirable fuel density and viscosity, a comparable or slightly higher heating value, lower cetane number, oxidation stability, and good performance in cold temperatures. These characteristics contribute to reduced emissions, efficient combustion, favorable flow properties at low temperatures, and excellent oxidation stability in biodiesel (Arguelles et al. 2018).

On the other hand, Nautiyal et al. (2014) determined the fuel properties of *Spirulina* algae biodiesel and pond water algae biodiesel, as shown in Table 11. The density of the *Spirulina* biodiesel sample in their study was found to be 860 kg/m^3, while that of the pond water algae biodiesel was 870 kg/m^3. The viscosity of biodiesel obtained from *Spirulina platensis* and pond water algae was measured at 5.66 mm^2/s and 5.92 mm^2/s, respectively, which is lower compared to biodiesel derived from waste rapeseed oil and fish oil (6.35 mm^2/s and 7.2 mm^2/s, respectively) (Aryee et al. 2009; Yuan et al. 2008). Density and viscosity of a particular fuel impact brake-specific fuel consumption. Higher density and viscosity result in a greater mass of injected fuel, leading to increased brake-specific fuel consumption. Additionally, higher values of density and viscosity can cause poor atomization and inadequate air–fuel mixing, resulting in inefficient combustion and reduced engine efficiency.

The microalgae strain selection is crucial for biodiesel production (Chye et al. 2018), as factors such as cetane number, viscosity, calorific value, and melting point determine the quality of biodiesel and its performance in engines. Bioengineering of microalgae strains is a proposed method to enhance biodiesel quality (Nigam and Singh 2011). However, crude oil extracted from algae has a higher viscosity than diesel oil, making it unsuitable for direct use in engines. Therefore, transesterification is necessary to reduce the viscosity and improve the fluidity of algal oil. In the transesterification process, algal lipids, particularly triacylglycerides, are converted into biodiesel and glycerol with the help of alkali or acid (Sirajunnisa and Surendhiran 2016). Transesterification also involves the reaction between ester and alcohol, resulting in the formation of fatty acid-alcohol esters by replacing the alkoxy group. This chemical process breaks down triglycerides into diglycerides, monoglycerides, and, ultimately, glycerol. Transesterification of large and branched triglyceride molecules produces short and straight-chain esters (Milano et al. 2016). Figure 6 shows the process of biodiesel production from algae through transesterification.

Biodiesel production from microalgae stands as a significant and promising method to fulfill the global demand for transportation fuel. Biodiesel derived from microalgae can be readily employed in diesel engines with minimal adjustments and can be blended with petroleum diesel in varying ratios (Krishnasamy and Bukkarapu 2021). Table 12 illustrates the advantages of using algae as a feedstock for biodiesel production. Consequently, microalgae-based biofuels emerge as a pragmatic and economically feasible solution to address both the demand for fuel and environmental apprehensions (Ali et al. 2022; Tang et al. 2020). However, challenges remain in the collection

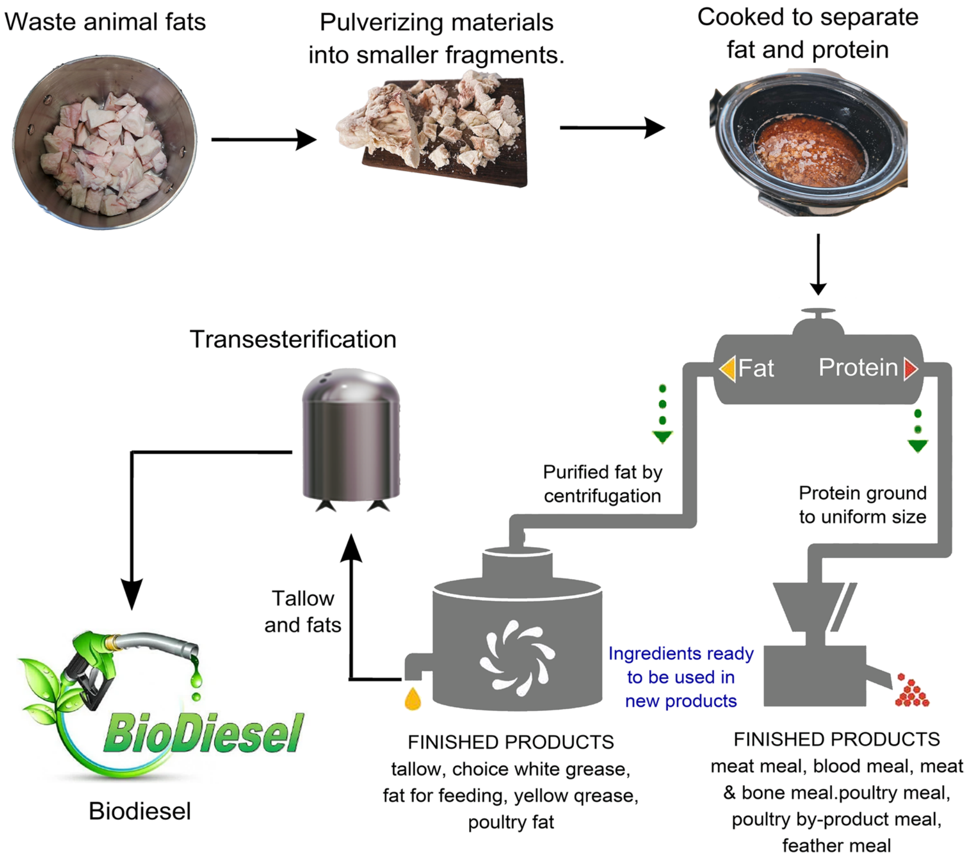

Fig. 5 Biodiesel production from waste animal fat using transesterification process. Biodiesel production from waste animal fat involves several key steps to convert the waste material into usable fuel. These steps include pulverizing the waste animal fat to facilitate the extraction of fats and proteins. The pulverized fat is then cooked under controlled conditions to separate the fats from the solid residue, such as proteins and other impurities. The cooked material is subjected to pressure to separate the fats from the solid residue, extracting the tallow, which is rich in fats and can be used as a feedstock for biodiesel production. The extracted tallow is mixed with an alcohol, typically methanol or ethanol, in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide, to form fatty acid esters and glycerol, creating biodiesel. The glycerol and biodiesel mixture are separated through a settling tank or centrifugation, and glycerol, a by-product, can be used in various applications, such as in the cosmetic and pharmaceutical industries. The biodiesel is washed with water to remove any remaining catalyst and impurities, dried to remove excess water, and tested for its properties. By following these steps, waste animal fat can be efficiently converted into biodiesel, providing a sustainable and eco-friendly alternative to fossil fuels and contributing to the reduction of environmental pollution

process and carbon dioxide preparation for optimal production (Rahpeyma and Raheb 2019).

Fish waste

Marine species like cod, tuna, and squid, known for their rich polyunsaturated fatty acids, particularly C20:5 and C22:6, often have higher lipid content in red-flesh varieties, with fish livers being particularly lipid-rich. However, the discarded parts of marine fish, such as viscera, fins, eyes, and tails, are usually ground into fishmeal for livestock, aquaculture, or pet food due to their limited economic value. Additionally, the fishery industry produces oils rich in omega-3 fatty acids for human consumption, resulting in approximately 45% of the caught fish being discarded after omega-3-rich oil extraction. These discarded materials, including viscera skin, accounting for 1.4–40.1% (w/w) of the oil content, can be effectively used to produce bio-oil or biofuels (Kumari et al. 2022). Fish waste contains saturated, monounsaturated, and polyunsaturated fatty acids in concentrations suitable for producing high-quality biodiesel. The crude fish oil extracted from these discarded parts serves as an abundant, cost-effective, and stable source of raw oil for biodiesel production, offering maritime countries a means to reduce pollutant emissions (Kiehbadroudinezhad et al. 2023; Lin and Li 2009). The extracted fish oil can be converted to fish oil methyl ester (FOME) and fish oil ethyl ester (FOEE) by transesterification with methanol and ethanol, respectively. The biodiesel derived from fish waste meets regulatory agency standards and is well-suited for storage and transportation. Table 13 summarizes the fuel properties of biodiesel

Table 9 Advantages and challenges of using waste animal fat as a feedstock for biodiesel production

Parameter	Waste animal fats as a feedstock for biodiesel production	References
Advantages	Renewable and sustainable: Waste animal fats, which are derived from by-products like used cooking oil, grease, or discarded fats, offer an opportunity for sustainable biodiesel production. Instead of being disposed of as waste, these materials can be utilized, making the biodiesel production process environmentally friendly and sustainable Cost-effectiveness: Waste animal fats are often acquired at a lower cost or even free of charge since they are considered waste materials. By using these fats as a feedstock for biodiesel production, significant reductions in overall production costs can be achieved, making biodiesel a more economically viable alternative fuel High energy content: Waste animal fats have a high energy content, increasing biodiesel yields. The elevated energy density of animal fats contributes to the efficiency and performance of biodiesel as a fuel Positive fuel characteristics: Biodiesel produced from waste animal fats exhibits desirable fuel properties, including good lubricity, a high cetane number (indicating improved combustion characteristics), and low sulfur content. The octane number of the fats-based biodiesel is greater than 50, making the ignition quality better than the conventional fuel. The flash point is the temperature at which fuel gets ignited. The flash point temperature of animal-based biodiesel is 150 °C, which is better safety while storing or transporting. These characteristics make waste animal fat-based biodiesel a suitable replacement for conventional diesel fuel Waste management: Using animal fats for biodiesel production contributes to effective waste management by diverting these fats away from landfills or improper disposal methods. This approach promotes the concept of a circular economy and reduces the environmental impact associated with waste disposal Offsetting carbon dioxide emissions: Biodiesel derived from waste animal fats is considered carbon neutral since the carbon dioxide emitted during combustion is offset by the carbon dioxide absorbed by the feedstock source. The polycyclic aromatic hydrocarbon emission reduces up to 75–90% in the case of animal fat-based biodiesel. This mitigates the overall carbon footprint and aids in addressing climate change	Aniokete et al. (2022), Habib et al. (2020, 2022), Srinivasan et al. (2020, 2022), Toldrá-Reig et al. (2020b)
Challenges	Biodiesel production from animal fat must adhere to specific quality standards and certifications, which introduces complexity and additional costs to the production process. Meeting these requirements adds further intricacy to biodiesel production from animal fat The availability of animal fat can be uncertain and restricted due to its demand in other industries, such as pet food and cosmetics. This limited availability adds to the unpredictability of sourcing animal fat for biodiesel production The quality of animal fat can differ considerably based on factors such as the animal's health, diet, and processing methods. This variation can pose challenges in ensuring consistent biodiesel production and may necessitate additional refining processes to meet fuel quality requirements	Alajmi et al. (2018), Habib et al. (2020), Ramos et al. (2019), Srinivasan et al. (2020)

The table underscores the feedstock's renewable and sustainable character, cost-effectiveness, high energy content, positive fuel characteristics, waste management benefits, and offsetting carbon dioxide emissions as its primary advantages. Biodiesel from waste animal fats possesses positive fuel characteristics like good lubricity, a high cetane number, and low sulfur content, rendering it a viable substitute for traditional diesel fuel. However, contrasting these advantages are notable challenges: inconsistencies in fat quality, restricted availability owing to competing demands in diverse industries, and the necessity to comply with stringent quality standards. These challenges pose complexities and increased costs within the biodiesel production process, thereby requiring meticulous attention and resolution strategies

Table 10 Advantages and challenges of using waste vegetable oil as a feedstock for biodiesel production

Parameter	Waste vegetable oil as a feedstock for biodiesel production	References
Advantages	Ensuring environmental sustainability: Waste vegetable oil originates from the cooking and food processing industries, and employing it as a feedstock for biodiesel production reduces waste accumulation in landfills and improper disposal. This approach effectively manages and repurposes waste materials, thereby promoting environmental sustainability Renewable and sustainable source: Waste vegetable oil is derived from vegetable oils obtained primarily from plant sources like soybeans, canola, or palm. These vegetable oils are renewable resources that can be replenished through agricultural practices. By utilizing waste vegetable oil as a feedstock, biodiesel production becomes a sustainable process that relies on an abundantly available source Cost-effectiveness: Waste vegetable oil is frequently obtainable at lower costs or even free of charge, as it is a byproduct of food-related industries. This makes it a cost-effective feedstock for biodiesel production, particularly when compared to unused vegetable oils. The utilization of waste vegetable oil helps to reduce overall production costs and contributes to making biodiesel a more economically viable alternative to fossil fuels Compatibility with existing infrastructure: Biodiesel produced from waste vegetable oil can be seamlessly blended with conventional diesel fuel or used independently in existing diesel engines without necessitating major modifications or infrastructure changes. This compatibility facilitates a smooth transition and adoption of biodiesel as an alternative fuel, as it can be readily used in current transportation and industrial sectors Advancing energy independence and security: Countries can decrease their reliance on imported fossil fuels by utilizing waste vegetable oil as a feedstock for biodiesel production. This enhances energy independence and security by utilizing locally available waste resources to fulfill a portion of their energy demands, reducing dependence on volatile international oil markets Carbon neutrality: Biodiesel derived from waste vegetable oil exhibits a significantly lower carbon footprint than conventional fossil-based diesel fuels. Waste vegetable oil-based biodiesel reduces emissions of greenhouse gases like carbon dioxide, sulfur dioxide, and particulate matter. This reduction contributes to mitigating climate change and improving air quality, promoting a cleaner and more sustainable environment	Chavan et al. (2017), Glisic et al. (2016), Hajjari et al. (2017), Thomas et al. (2020), Topi (2020), Tshizanga et al. (2017)

Table 10 (continued)

Parameter	Waste vegetable oil as a feedstock for biodiesel production	References
Challenges	Waste vegetable oil often contains impurities like water, food particles, and cooking-related contaminants. To maintain consistent fuel quality, these impurities must be eliminated or treated before using the oil for biodiesel production Securing a reliable and adequate supply of waste vegetable oil for biodiesel production can be difficult due to varying availability and limited quantities, especially in regions with minimal food-related waste Collecting and managing waste vegetable oil from various sources can be logistically complex. It requires establishing efficient collection systems, coordinating with multiple suppliers, and implementing appropriate storage and transportation methods to ensure the feedstock's quality and integrity. These considerations can add complexity and expenses to the biodiesel production process The composition and quality of waste vegetable oil can vary which can affect the efficiency of biodiesel production and the final product's quality. Implementing quality control measures becomes vital to ensure consistent feedstock quality and meet the desired specifications for biodiesel Regulatory compliance adds further challenges as biodiesel production from waste vegetable oil must meet quality specifications and adhere to environmental regulations. Meeting these compliance standards may involve additional testing, monitoring, and documentation processes, which can impose administrative burdens and potential costs on biodiesel production operations	Ortiz Lechuga et al. (2020), Tshizanga et al. (2017)

The advantages include promoting environmental sustainability by reducing waste accumulation and, repurposing waste materials, utilizing a renewable and sustainable source that can be replenished through agricultural practices. Furthermore, its cost-effectiveness, compatibility with existing infrastructure, contribution to local energy independence, and promotion of carbon neutrality by reducing emissions and enhancing air quality are key advantages. However, challenges exist in maintaining consistent fuel quality by removing impurities from waste vegetable oil, securing a reliable and sufficient supply of waste vegetable oil, managing logistical complexities in collection and storage, addressing the variability in composition and quality, complying with regulations and standards, and managing additional costs and administrative burdens. These factors provide insights into the advantages and challenges of using waste vegetable oil as a feedstock for biodiesel production, highlighting the potential benefits and considerations of adopting this approach

from FOME and FOEE for some published studies. Crude fish oil, with its high unsaturated fatty acid content, can enhance the low-temperature fluidity of biodiesel and prevent issues like cold filter plugging point (CFPP), sticking, freezing, and vehicle stalling that can occur when using biodiesel in cold climates. Conversely, biodiesel produced from raw oil with a high saturated fatty acid content, such as palm oil or animal fat, often exhibits a high CFPP and reduced fuel fluidity (Ching-Velasquez et al. 2020; Knothe 2005).

However, utilizing fish waste as a feedstock for biodiesel production presents several challenges. One major obstacle associated with fishery waste is its limited storage time, as the presence of enzymes and microbes within the waste can lead to lipid degradation. To address this challenge effectively, establishing biofuel production facilities in proximity to fishery industries can not only reduce the cost of biofuel production but also mitigate the environmental impact of fishery waste disposal (Kumari et al. 2022). Additionally, there are significant challenges related to the processing of fish waste. Fisheries primarily concentrate on their core profitable operations and may not explore alternative applications for their waste, especially if waste disposal is cost-effective and straightforward. Implementing new technologies often becomes economically viable only at a large scale, which may not align with the operations of small and dispersed fishing enterprises. The seasonality and perishability of fish waste also present hurdles, as specific products and waste materials are only available during particular months, resulting in inconsistent feedstock supply. Furthermore, biological waste can encompass various residues and potential contaminants, increasing the cost of pretreatment. Complex waste regulations further impede progress, as businesses may hesitate to explore different regulatory approaches, affecting their decisions regarding the utilization of fish waste (Rudovica et al. 2021).

Table 11 Fuel properties of different species of algae biodiesel and standard diesel

Fuel properties	Unit	*Desmodesmus* sp. (I-AU1) biodiesel Arguelles et al. (2018)	*Spirulina* biodiesel Nautiyal et al. (2014)	Pond water algae biodiesel Nautiyal et al. (2014)	ASTM D6751 Fonseca et al. (2019)	EN 14214 Fonseca et al. (2019)
Density	kg/m^3	880	860	872	Not available	860–900
Kinematic viscosity	mm^2/s	2.81	5.66	5.82	1.9–6	3.5–5
Specific gravity	-	Not available	0.865	0.878	0.88	Not available
Cetane number	-	43.47	Not available	Not available	Greater than or equal to 47	Greater than or equal to 51
Acid number	mgKOH/gm	Not available	0.45	0.4	Less than or equal to 0.5	Less than or equal to 0.5
Calorific value	MJ/kg	37.73	41.36	40.80	Not available	Not available
Iodine value	(gI$_2$/100 gm)	120.4	Not available	Not available	Not available	Less than or equal to 120
Pour point	°C	Not available	− 18	− 16	− 15 to − 16	Not available
Flash point	°C	Not available	130	Not available	Greater than or equal to 130	Greater than or equal to 101
Saturated fatty acids	%	31.02	Not available	Not available	Not available	Not available
Monounsaturated fatty acids (MUFA)	%	25.64	Not available	Not available	Not available	Not available
Polyunsaturated fatty acids (PUFA)	%	43.39	Not available	Not available	Not available	Not available

The properties examined include density, kinematic viscosity, specific gravity, cetane number, acid number, calorific value, iodine value, pour point, flash point, saturated fatty acids, monounsaturated fatty acids, and polyunsaturated fatty acids (PUFA). The data highlights variations among *Desmodesmus sp.* (I-AU1), *Spirulina*, and pond water algae biodiesels, presenting parameters such as density ranging from 860 to 880 kg/m^3, kinematic viscosity from 2.81 to 5.82 mm^2/s, and cetane number greater than or equal to 47. Standard specifications ASTM D6751 and EN 14214 are also referenced to showcase the standards for comparison. ASTM refers to the American Society for Testing and Materials, and EN refers to the European Standard

Municipal solid waste

Rapid industrialization and urbanization globally are putting pressure on urban areas to manage the waste generated. Solid waste is an inevitable byproduct of industrial processes, encompassing a wide range of materials, and managing it sustainably poses a significant challenge (Kowalski et al. 2022). An estimate suggests that 1.3 billion tons of municipal solid waste is currently generated, which is projected to increase to 2.2 billion tons by 2025. The cost of disposing of municipal solid waste is significant, ranging from 10 to 30 USD per ton. Global municipal solid waste accounts for nearly 5% of global emissions, equivalent to approximately 1.6 billion tons of carbon dioxide. If the current trend of municipal solid waste production continues, waste generation is predicted to increase by 70% by 2050, resulting in a 62% increase in global emissions (Velvizhi et al. 2020). Thus, municipal solid waste contributes to high pollution levels and adversely affects public health.

Globally, the composition of municipal solid waste consists of 44% food and green waste, 17% paper and cardboard, 12% plastics, 5% glass, 4% metal, 2% wood, 2% rubber and leather, and 14% other materials. The organic portion of solid waste from municipalities, known as OF-MSW, contains a significant amount of biodegradable materials and is readily available at no or low cost. Globally, approximately 2 billion tons of municipal solid waste is generated annually, with OF-MSW accounting for 34–53% of this waste. OF-MSW primarily includes waste from food manufacturing, household scraps from food preparation, leftovers, expired food, and waste from restaurants and food outlets. These sources contribute to 39%, 42%, and 19% of the total European Union food waste stream, respectively (Mozhiarasi and Natarajan 2022). The current management strategies for OF-MSW, such as landfilling and composting, result in unpleasant odors and pollution of land and groundwater. Thermochemical technologies like incineration, gasification, and pyrolysis have been widely used to efficiently convert OF-MSW into energy and chemicals. However, the high energy requirements, use of fossil fuels, production of corrosive byproducts like bio-oils, and the release of pollutants such as carbon monoxide and carbon dioxide undermine the environmental benefits of energy production from OF-MSW using thermochemical methods (Ebrahimian et al. 2020). Therefore, utilizing OF-MSW, consisting

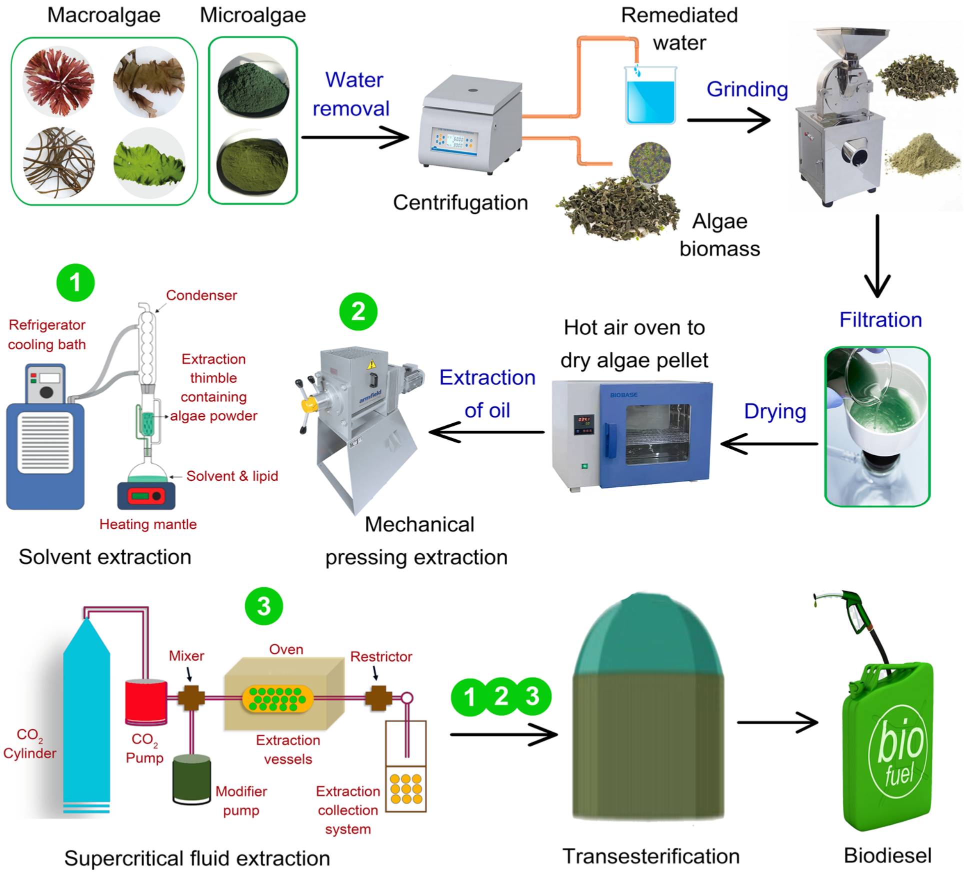

Fig. 6 Biodiesel production from algae using the transesterification process. This process encompasses critical stages such as water removal, grinding, filtration, drying, oil extraction techniques like solvent extraction, mechanical pressing extraction, and supercritical fluid extraction. Each step plays a vital role in extracting and refining the oil content from algae to produce biodiesel. Water removal ensures minimal moisture content in the biomass, while grinding breaks down the algae to increase surface area for extraction. Filtration removes unwanted particles, and drying further prepares the algae for oil extraction using various methods like solvent, mechanical pressing, or supercritical fluid extraction. Finally, the transesterification process converts the extracted oil into biodiesel, contributing to a sustainable and renewable fuel source

Table 12 Advantages and challenges of using algae as a feedstock for biodiesel production

Parameter	Algae as a feedstock for biodiesel production	References
Advantages	Algae adapt to various habitats, including ponds, bioreactors, and wastewater treatment plants. This versatility reduces the need for arable land and expands the potential for algae cultivation	Anerao et al. (2022), Kesharvani and Dwivedi (2021)
	Algae demonstrate rapid growth rates and yield a higher oil content than other sources, making them incredibly efficient for biodiesel production	
	Algae play a crucial role in carbon dioxide sequestration as they consume carbon dioxide during photosynthesis, providing a means to offset greenhouse gas emissions and making it a more sustainable and greener solution	
Challenges	Advanced technologies are necessary to implement algae cultivation and utilize it commercially, which can incur additional expenses	Jabłońska-Trypuć et al. (2023), Scott et al. (2010)
	The susceptibility of algae cultivation systems to contamination by various microorganisms can hinder the efficiency of the process and lead to lower yields	
	Extracting lipids from algae during the biodiesel production process adds to the overall expenses, making it a more costly option compared to other biofuel sources	

Algae exhibit adaptability to diverse habitats such as ponds, bioreactors, and wastewater treatment plants, thereby diminishing the necessity for arable land and broadening the scope for cultivating algae. Additionally, they boast rapid growth rates and a higher oil yield compared to other sources, rendering them highly efficient for biodiesel production. Moreover, algae play a pivotal role in carbon dioxide sequestration during photosynthesis, offering a sustainable and greener approach to offset greenhouse gas emissions. Conversely, challenges related to algae utilization encompass the requirement for advanced, cost-intensive technologies for large-scale cultivation. Moreover, susceptibility to microbial contamination in algae cultivation systems poses an impediment to efficiency, potentially leading to reduced yields. Furthermore, the extraction of lipids during biodiesel production from algae escalates overall expenses, rendering it a relatively costly option compared to other biofuel sources

Table 13 Fuel Properties of biodiesel from fish oil methyl ester and fish oil ethyl ester

Fuel properties	Units	FOME Kathirvelu et al. (2017)	FOME Ching-Velasquez et al. (2020)	FOME Fadhil et al. (2017)	FOEE Fadhil et al. (2017)
Density	kg/m^3	890	890	883.4	889.7
Kinematic viscosity	mm^2/s	5.2	5.3	3.28	4.18
Acid number	mgKOH/gm	0.9	Not available	0.25	0.31
Pour point	°C	Not available	Not available	− 1	1
Calorific value	MJ/kg	38.7	38.1	Not available	Not available
Flash point	°C	157	Not available	94	105
Cetane number	–	53	Not available	Not available	Not available
Cloud point	°C	Not available	10.5	5	6

The table presents properties like density, kinematic viscosity, acid number, pour point, calorific value, flash point, cetane number, and cloud point for both fish oil methyl ester and fish oil ethyl ester. Analyzing properties like density, kinematic viscosity, acid number, and others for fish oil methyl ester and fish oil ethyl ester helps in assessing their applicability in biodiesel production. Parameters such as pour point, calorific value, flash point, cetane number, and cloud point offer crucial insights into the fuel properties of both fish oil methyl ester and fish oil ethyl ester, assisting in evaluating their suitability as biodiesel alternatives. FOME refers to fish oil methyl ester, and FOEE refers to fish oil ethyl ester

mainly of starchy and lignocellulosic waste, as a renewable feedstock for bioenergy and bioplastic production through biological conversion offers sustainable alternatives to fossil fuels and petroleum-based polymers. A pretreatment step is necessary to enhance the biodegradability of OF-MSW due to the inherent resistance of the lignocellulosic fraction (Ebrahimian et al. 2020). The European Union has implemented directives to reduce waste generation, promote recycling, encourage source separation, and minimize the amount of biodegradable waste sent to landfills to improve sustainability in municipal solid waste management (Abad et al. 2019). Instead of using various disposal methods, it is recommended that municipal solid waste be utilized to produce biodiesel.

Food waste is the dominant component of OF-MSW, and its characteristics, including chemical and physical composition, vary globally due to regional variations in diets and waste production and processing methods (Capson-Tojo et al. 2016). These differences challenge establishing international standards for food waste disposal, recycling, and valorization (Pour and Makkawi 2021). Addressing the mismanagement of municipal solid waste, particularly OF-MSW (food and green waste), is becoming increasingly important, especially in developing nations. A significant amount of food is wasted annually, and improper food waste disposal leads to negative environmental impacts, such as greenhouse gas emissions, particularly methane, which has a much higher global warming potential than carbon dioxide. Adopting a market-based approach for municipal solid waste recycling and resource recovery, including the organic fraction, could generate substantial economic benefits (Sharma and Dubey 2020). Various researchers conducted several studies to produce biodiesel with great properties from food waste. In this context, Su et al. (2010) obtained separated floating oil after subjecting the food waste feedstock to crushing and high-temperature boiling. The oil was black with some impurities and a rancid odor. Subsequently, the waste oil underwent a refining process. The composition of the resulting oil showed a higher proportion of octadecenoic acid (44.74%), octadecadienoic acid (14.%), and hexadecanoic acid (30.89%). The specific weight, saponification value, acid value, and average molecular weight of the oil were determined to be 0.915 g/cm^3, 207 mg/g, 2.955 mg KOH/g, and 825 g/mol, respectively. These observed values suggest that this particular feedstock could be considered a suitable substrate for biodiesel production. Barik et al. (2018) used an innovative approach to utilize kitchen food waste for biodiesel production. Food waste was dewatered, and lipid was extracted using methanol as a solvent with a yield of 37.3%. Lipid analysis was performed in gas chromatography-mass spectrometry (GC–MS) to identify the fatty acids. Lipids were further transesterified using methanol as solvent and sulphuric acid as catalyst, producing a fatty acid methyl ester yield of 33.2%. Physical and chemical properties of biodiesel were investigated and found calorific value of 31.38 MJ/kg, density of 872 kg/m^3, viscosity of 2.2 mm^2/s, flash point of 164 °C, pour point of 7 °C, cloud point of 12 °C, and acid value of 0.63 mgKOH/g.

Biodiesel production from lipids extracted from OF-MSW, using a solvent-to-waste ratio of 2:1, shows promise. The quality of biodiesel depends on the ratio of saturated to unsaturated fatty acids, with a higher saturated fraction leading to lower quality and potential engine problems (Velvizhi et al. 2020). Biodiesel derived from OF-MSW is considered carbon neutral, non-toxic, biodegradable, and sustainable (Dhiman and Mukherjee 2020). Karmee et al. (2015) conducted a study on the use of lipids derived from food waste as an economical feedstock for biodiesel production. The lipid obtained from food waste was subjected to transesterification with methanol, employing base and lipase catalysts. The highest biodiesel yield of 100% was achieved through base-catalyzed transesterification using potassium hydroxide, with a lipid-to-methanol molar ratio of 1:10, at a temperature of 60 °C within a 2h timeframe. When novozyme-435 was used as the catalyst, fatty acid methyl ester conversion of 90% was obtained at a temperature of 40 °C and a lipid-to-methanol molar ratio of 1:5, with a reaction duration of 24 h. The lipid derived from fungal hydrolysis of food waste was determined to be a suitable feedstock for biodiesel production.

Besides utilizing OF-MSW as a feedstock for biodiesel production, several agricultural wastes show promise as potential sources for biodiesel production. Examples of such waste include tea seed, tobacco seed, tomato seed, linseed, bay laurel leaves and fruits, and cherry seed. Additionally, non-conventional seed oils like corn germ oil, rice bran oil, cherry laurel seed oil, and date palm seed can also be used. Seed oils with high levels of free fatty acids are typically employed in a two-step biodiesel production process. The first step involves catalytic acid esterification to reduce the free fatty acid content to below 2%. In the second stage, an alkali catalytic transesterification process converts the products from the first step into biodiesel. Currently, there are abundant resources of tobacco seed, tea seed, and corn germ globally, making them attractive options for producing cost-effective biodiesel (Rehan et al. 2018). Using municipal solid waste for biodiesel production provides numerous advantages and benefits. In addition, several limitations and challenges are associated with using municipal solid waste as feedstock for biodiesel production, as shown in Table 14. Despite these challenges, research and technological advancements are ongoing to develop more efficient and cost-effective methods for utilizing municipal solid waste as a feedstock for biodiesel production.

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Municipal sewage sludge

Sewage sludge, a significant form of biowaste generated in wastewater treatment plants (Feng et al. 2023), poses environmental challenges as it is currently underutilized and lacks a clear solution. Wastewater treatment plants treat approximately 60% of municipal wastewater worldwide, producing substantial amounts of sewage sludge (Barreiro et al. 2022). The management of sewage sludge is an urgent problem, with European countries producing an estimated 0.1–30.8 kg of sludge per population equivalent per year (Menezes et al. 2022). In Europe, sludge disposal primarily occurs through agricultural use (34%) and incineration (33%) (Lozano et al. 2022). Global municipal wastewater generation is projected to increase by 24% and 51% by 2030 and 2050, respectively. The European Union, the United States, and China are major producers of sewage sludge, with annual production rates of approximately 50 million tons, 40 million tons, and 60 million tons, respectively (Hu et al. 2022; Siddiqui et al. 2023).

This waste consists of two main types: primary sludge, which contains organic matter and suspended solids, and waste-activated sludge, composed of various microorganisms (Barreiro et al. 2022; Liew et al. 2023a). Anaerobic digestion can partially convert mixed and stabilized sludge into biogas containing methane, carbon dioxide, and other gases (Mateo-Sagasta et al. 2015; Snowden-Swan et al. 2016). However, conventional treatment methods such as incineration and landfilling (Odirile et al. 2021) have negative environmental impacts and fail to completely remove organic pollutants (Alvim et al. 2020; Amin et al. 2021; Khalil et al. 2020; Mohamed et al. 2023). To address these challenges, there is growing interest in utilizing sewage sludge for biodiesel production (Huang et al. 2023; Zhao et al. 2022). Lipids present in the sludge can be converted into biodiesel through processes like lipid extraction, esterification, and transesterification (Siddiqui et al. 2023), as shown in Fig. 7. However, the high moisture content of sludge poses a significant obstacle, as it increases the cost of biodiesel production. Dry sludge or innovative techniques are necessary to overcome this barrier. Studies have shown that sewage sludge contains 5–20% fat, comparable to the fat content found in plant seeds, with biodiesel production efficiency ranging from 4 to 20% (Babayigit et al. 2018; Joorasty et al. 2022).

Researchers have explored different approaches to synthesizing biodiesel from sewage sludge, including two-step lipid extraction, transesterification/esterification, and in-situ processes from dry or wet sludge. The first approach is more profitable but generates residual sludge contaminated with organic solvents, creating new waste management challenges. The sustainable and efficient recovery of lipids remains a crucial hurdle for the profitable use of sewage sludge as a biodiesel feedstock (D'Ambrosio et al. 2021; di Bitonto et al. 2020; Scelsi and Pastore 2023; Villalobos-Delgado et al. 2021). Some studies have investigated the use of sewage sludge as a growth substrate for oleaginous microorganisms to accumulate lipids for biodiesel production. However, further research is needed to optimize lipid content and biodiesel yield. The decision between the direct use of sewage sludge for biodiesel production and indirect use through lipid accumulation requires evaluation throughout the entire lifecycle (Siddiqui et al. 2023; Venditti et al. 2020).

In a recently published article, Usman et al. (2023) conducted a study on the utilization of wet sewage sludge in

Table 14 Advantages and challenges of using municipal solid waste as feedstock for biodiesel production

Parameter	Municipal solid waste as a feedstock for biodiesel production	References
Advantages	Abundant and renewable resources: Municipal solid waste is a readily available and plentiful resource generated daily. This makes it a dependable and renewable feedstock for biodiesel production Waste management solution: Municipal solid waste presents significant challenges in waste management and disposal. Utilizing municipal solid waste for biodiesel production offers an environmentally friendly solution to the waste management problem. This approach reduces landfill volumes and minimizes associated environmental risks Energy independence: Biodiesel derived from municipal solid waste decreases reliance on fossil fuels for energy. It is an alternative fuel source for diesel engines, reducing dependence on traditional petroleum-based diesel and contributing to energy independence Reduction in greenhouse gas emissions: Biodiesel produced from municipal solid waste significantly reduces greenhouse gas emissions compared to fossil fuels. Since OF-MSW primarily comprises organic waste, converting it into biodiesel helps mitigate climate change by minimizing carbon dioxide emissions and other harmful pollutants Promotion of local economic development: Utilizing municipal solid waste for biodiesel production can stimulate local economic growth. It creates new job opportunities in waste collection, sorting, processing, and the biodiesel production industry. Additionally, it reduces the need to import fossil fuels, helping retain money within the local economy Encouragement of waste diversion and recycling: Municipal solid waste contains various recyclable materials like plastics, paper, and metals. However, a significant portion of municipal solid waste often goes unrecycled. Using OF-MSW for biodiesel production encourages waste diversion and promotes the recycling of other valuable materials in the waste stream Energy recovery: Biodiesel production from municipal solid waste involves a process called thermochemical conversion, which recovers energy from the waste. Through processes like pyrolysis or gasification, the non-organic components of municipal solid waste can be converted into syngas or other forms of energy, which can be further utilized for electricity generation or other applications Waste-to-energy solution: Biodiesel production from municipal solid waste represents a waste-to-energy solution. It maximizes the energy potential of the waste material and simultaneously addresses waste management and energy demands. This approach aligns with the principles of a circular economy by converting waste into a valuable resource	Abubakar et al. (2022), Amen et al. (2021), Aracil et al. (2017), Ebrahimian et al. (2020), Gaeta-Bernardi and Parente (2016), Velvizhi et al. (2020)

Table 14 (continued)

Parameter	Municipal solid waste as a feedstock for biodiesel production	References
Challenges	Contaminants and impurities: Municipal solid waste can contain many contaminants and impurities, such as heavy metals, plastics, glass, and non-biodegradable materials. These impurities can interfere with the biodiesel production process, leading to reduced efficiency, increased equipment wear, and the need for extensive pre-processing and refining steps	Hasan et al. (2021), Naveenkumar et al. (2023), Sajid et al. (2022), Wang et al. (2023), Yu et al. (2023)
	Heterogeneous composition: Municipal solid waste is a mixture of various waste materials, which makes it difficult to achieve consistent and standardized feedstock quality. The varying composition of municipal solid waste can affect the yield and quality of biodiesel produced, requiring careful sorting and separation of different waste streams	
	Low lipid content: Compared to traditional biodiesel feedstocks like vegetable oils and animal fats, municipal solid waste generally has a lower lipid content. Lipids are the primary components that can be converted into biodiesel. Therefore, large volumes of municipal solid waste may be required to obtain significant biodiesel yields, necessitating efficient extraction methods	
	Feedstock availability and consistency: The availability and consistency of municipal solid waste as a feedstock can be challenging. Waste generation rates may fluctuate, and there may be variations in the types and quality of waste depending on the region, season, and waste management practices. Ensuring a consistent and reliable supply of suitable municipal solid waste feedstock can be a logistical challenge	
	Environmental considerations: While municipal solid waste can be a potential feedstock for biodiesel production, its utilization should be assessed in terms of environmental sustainability. The collection, transportation, and processing of municipal solid waste can have environmental impacts, and the overall carbon footprint of the biodiesel production process should be considered	

Advantages include municipal solid waste abundance and renewable nature, contributing to sustainable biodiesel creation. Municipal solid waste acts as an effective waste management solution, reducing landfill use and potentially lessening dependency on fossil fuels for energy. Despite these advantages, hurdles such as impurities, the varied composition of municipal solid waste, its lower lipid content, and the need for consistent feedstock availability pose significant challenges in optimizing biodiesel production from municipal solid waste. Additionally, the environmental impacts of waste collection and processing are crucial aspects to consider when harnessing municipal solid waste for biodiesel production. OF-MSW refers to the organic portion of solid waste from municipalities

Tokyo for biodiesel production. The researchers examined the extraction of saponifiable lipids from the wet sludge and investigated the effects of acid and base catalysts. Two different sludge samples, namely plant A from an urban area and plant B from a suburban area, were used in the study. Their findings demonstrated that saponifiable lipids can be successfully extracted from raw wet sludge, resulting in biodiesel yields of approximately 97% and 99% when base and acid transesterification methods were employed, respectively. Gas chromatography–mass spectrometry analysis revealed a higher concentration of free fatty acids, triglycerides, and esters, with an estimated 99.9% yield of fatty acid methyl ester. Interestingly, both plants displayed similar results in terms of saponifiable lipids extraction and biodiesel yields. However, the physicochemical properties of the biodiesel derived from the plant A sludge were further investigated. The biodiesel exhibited a density of 0.881 g/cm^3, viscosity of 4.152 mm^2/s, a calorific value of 39.25 MJ/kg, and a sulfur content of 2 ppm. On the other hand, the biodiesel derived from plant B sludge had a density of 0.881 g/cm^3, viscosity of 3.877 mm^2/s, a calorific value of 38.86 MJ/kg, and a sulfur content of 112 ppm. Based on these results, the fatty acid methyl ester obtained from the Plant A sludge (urban area) shows potential as a fuel feedstock candidate, as its sulfur content falls within the standard fuel concentration limit. However, plant B sludge (suburban area) exhibited a high sulfur content, indicating that a desulfurization step would be necessary if this sludge were to be used as a fuel feedstock.

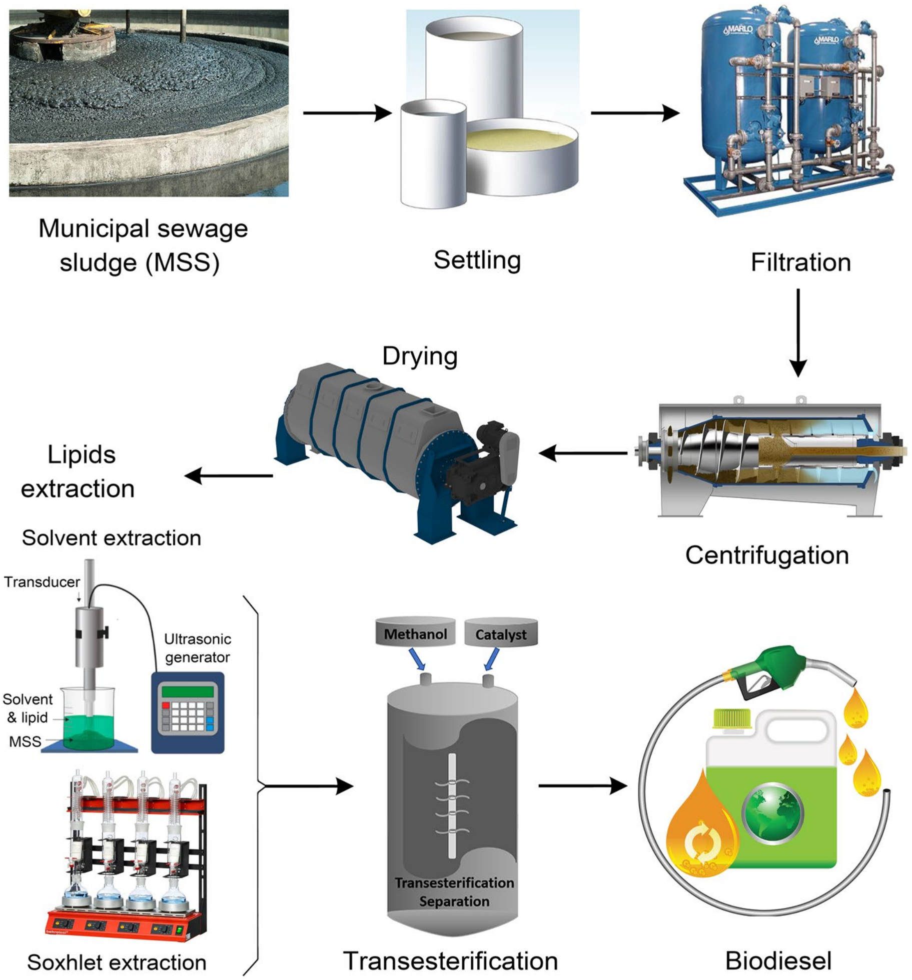

Fig. 7 Biodiesel production from municipal sewage sludge using transesterification process. The figure illustrates the biodiesel production process from municipal sewage sludge using the transesterification method, incorporating several pretreatment and conversion steps. The pretreatment processes include settling, filtration, and centrifugation, which are employed to remove solid impurities and separate the desired lipids from the sludge. The next step involves lipid extraction using solvent extraction or Soxhlet extraction techniques, enabling the isolation of lipids from the sludge for subsequent conversion. The final stage involves transesterification, where the extracted lipids are reacted with alcohol and a catalyst to produce biodiesel. This process facilitates the conversion of sewage sludge, a waste resource, into a valuable and sustainable biofuel. MSS refers to municipal sewage sludge

Similarly, Patiño et al. (2021) conducted a study on the production of biodiesel using sludge collected from wastewater treatment plants. The research revealed a strong correlation between the composition of fatty acid methyl esters and the properties of biodiesel, providing a convenient and efficient method to predict the fuel properties of biodiesel derived from other types of sludge based on their composition values. Furthermore, the physicochemical properties of the biodiesel obtained from the sludge were thoroughly investigated. The biodiesel exhibited a density of 0.916 g/cm^3, a viscosity of 2.6 mm^2/s, and a calorific value of 39.8 MJ/kg. These findings open up possibilities for predicting the properties of biodiesel obtained from different sludge sources, allowing for more efficient and informed utilization of sludge as a potential feedstock for biodiesel production.

Overall, sewage sludge represents a significant biomass waste that, with proper utilization, can contribute to renewable energy production and adhere to the principles of the circular economy. However, addressing the challenges of sewage sludge treatment and ensuring its economic and environmental feasibility requires continued research and innovation. The advantages and challenges of using municipal sewage sludge as a feedstock for biodiesel production are illustrated in Table 15.

Policy recommendations for encouraging biodiesel production from waste

Supportive policies are necessary to realize the full potential of biodiesel generation from waste materials. Governments and politicians must play a key role in fostering an environment that encourages the production and use of biodiesel made from trash. A solid government policy is essential for long-term social and economic growth. The government will be responsible for setting up an appropriate platform or medium for other stakeholders, including industry players, nongovernmental organizations, research institutions, and private investors, to contribute towards developing biofuel blends. Government policies will be crucial in areas like the subsidy program, tax relief, financial aid, information sharing, investment environment, authorization, and requirements of biofuel blends. Many biodiesel facilities were built in the past due to rising environmental consciousness fueling

Table 15 Advantages and challenges of using municipal sewage sludge as feedstock for biodiesel production

Parameter	Municipal sewage sludge as a feedstock for biodiesel production	References
Advantages	Waste utilization: Municipal sewage sludge is a waste product generated from wastewater treatment plants. Using municipal sewage sludge for biodiesel production provides a sustainable and environmentally friendly approach to utilize this waste material effectively, reducing the burden on landfills Feedstock availability: Municipal sewage sludge is abundantly available in urban areas where wastewater treatment plants are in operation. This availability makes it a convenient and cost-effective feedstock for biodiesel production, reducing the reliance on traditional feedstocks such as vegetable oils or animal fats Reduction of fossil fuel dependency: Biodiesel produced from municipal sewage sludge helps to reduce dependence on fossil fuels. It offers a renewable and alternative energy source that can be used in transportation and other applications, contributing to greenhouse gas emissions reduction and mitigating climate change Nutrient recycling: Sewage sludge contains valuable nutrients such as nitrogen and phosphorus. After extracting the lipids for biodiesel production, the remaining sludge can be used as a nutrient-rich fertilizer, promoting sustainable agriculture, and closing the nutrient cycle Carbon neutrality: Biodiesel produced from municipal sewage sludge has the potential to achieve carbon neutrality or even carbon negativity. By utilizing waste material and reducing emissions associated with fossil fuel use, the overall carbon footprint of biodiesel production can be significantly reduced	Liew et al. (2023b), Magalhães-Ghiotto et al. (2023), Mohamed and Li (2023), Usman et al. (2023)
Challenges	Heterogeneous composition: Municipal sewage sludge is a complex mixture that varies in composition depending on the source and treatment processes. This heterogeneity can affect the efficiency and consistency of biodiesel production, requiring additional pre-treatment steps to standardize the feedstock High moisture content: Municipal sewage sludge typically has a high moisture content, which can interfere with the transesterification process used to convert the lipids in the sludge into biodiesel. The removal of water from the sludge can be energy-intensive and add to the overall cost of biodiesel production High contaminant levels: Municipal sewage sludge can contain various contaminants, including heavy metals, pathogens, and organic pollutants. These contaminants can have detrimental effects on the catalysts used in the transesterification process and can also pose environmental and health risks if not properly managed Nutrient imbalance: While the nutrient content in municipal sewage sludge can benefit fertilizer application, the sludge's composition may not be well-balanced for optimal plant nutrition. Adjustments and additional treatments may be required to ensure the safe and effective use of the remaining sludge as a fertilizer Techno-economic feasibility: The overall techno-economic feasibility of biodiesel production from municipal sewage sludge is a major challenge. The high capital and operational costs associated with the necessary pre-treatment, dewatering, and purification steps can impact the economic viability of the process	Alsaedi et al. (2022), Bora et al. (2020), Kargbo (2010), Khan et al. (2022)

The advantages include the effective utilization of waste material, as municipal sewage sludge is a byproduct of wastewater treatment plants, reducing the burden on landfills. Its abundance in urban areas where wastewater treatment plants operate makes it a convenient and cost-effective feedstock, reducing reliance on traditional feedstocks. Biodiesel production from municipal sewage sludge helps reduce dependence on fossil fuels, offering a renewable and alternative energy source that contributes to greenhouse gas emissions reduction and climate change mitigation. Additionally, sewage sludge contains valuable nutrients that can be recycled as fertilizer, promoting sustainable agriculture and closing the nutrient cycle. Biodiesel produced from municipal sewage sludge has the potential to achieve carbon neutrality or even carbon negativity, further reducing the overall carbon footprint. However, challenges include the heterogeneous composition of sewage sludge, high moisture content that interferes with the transesterification process, high contaminant levels that require proper management, the nutrient imbalance that necessitates adjustments for safe fertilizer use, and the techno-economic feasibility of the overall biodiesel production process

demand for biofuels like biodiesel. However, as crude oil prices fell to around 30 USD per barrel, pricey biodiesel could not compete with mineral diesel, which caused its demand to decline significantly. As a result, most biodiesel manufacturing facilities were forced to close down or reduce their output. To avoid the same mistakes being made again in the future, policymakers will need to address the flaws mentioned above in the study made by (Masjuki et al. 2013). This article presents a set of policy recommendations to encourage and facilitate biodiesel production from waste, foster sustainability, and accelerate the transition to a greener and more resilient energy future.

Establishing renewable fuel standards

The scenario of out-of-place subsidies, in which governments pay subsidies on conventional fossil fuels instead of boosting the renewable sector to decrease the financial burden of global pricing, is a serious issue in most countries. These subsidies hamper the advancement of renewable technologies. Instead of continuing to use fossil fuels, it would be preferable to rationalize incentives for renewable energy sources to hasten the adoption of renewable technology. It's critical that renewable energy systems, including biodiesel plant setups, can be easily implemented in rural locations (Khan et al. 2021). In truth, there are useful lessons to be learned from other nations, both developed and developing alike. The European Union enacted the "Directive EC 2003/96" to achieve the legally mandated goal of 10% of all fuels placed on the market by 2020. According to the document's European Union regulations, petroleum diesel must be blended with biodiesel at a minimum share ratio of 5.75%, which greatly promotes the growth and use of biodiesel (Klessmann et al. 2011; Xu et al. 2016). Governments should set renewable fuel requirements that require a specific volume of waste-derived biodiesel in the overall diesel fuel supply. By guaranteeing a biodiesel market, this policy would encourage investment in manufacturing facilities as well as the collection and conversion of waste. Renewable fuel requirements give the biodiesel business long-term security and stability, spurring development, and market expansion.

Providing financial incentives

Financial incentives like tax credits, grants, and subsidies can greatly increase biodiesel production from garbage. Governments should financially support biodiesel producers, especially those who use trash. The financial sustainability of biodiesel initiatives can be increased while promoting research and development and helping offset the initial capital costs. The availability and accessibility of feedstock for the manufacture of biodiesel can also be improved by sponsoring programs that are explicitly aimed at garbage collection and preprocessing. Biodiesel is exempt from fuel tax in European Nations like France and Germany. Germany, France, and Italy are the top-producing nations of biodiesel in Europe, which is on top overall. Spain is the industry leader in Europe for the manufacturing of bioethanol. Along with these nations, other nations from different continents, including Brazil, Southeast Asia, and North America, have proposed new policies. As a result, scientists are given greater chances to scale up and commercialize their projects. The United States of America established a thorough standard policy on biodiesel industries in 1999. As a result of this policy, consumers now have more faith in biodiesel, which is a relatively new trend.

According to Shah et al. (2018), the Environmental Protection Agency in the United States of America (USEPA) had a significant role in pushing biodiesel as a viable alternative to petrol-diesel. In addition to the macro policies, certain specific activities include changing associated taxes, raising related investments, and setting related standards (particularly concerning oil quality). The amount of biofuels that qualify for tax credits has been established in countries including Belgium, France, Greece, Ireland, Italy, and Portugal. Tax credits are also granted in Austria, Belgium, and the Netherlands for mixed fuels, but only in Germany, the Czech Republic, and Luxembourg for pure biofuels. The majority of nations do, however, offer tax breaks for both markets. As part of a directive to develop biomass energy in the United States of America, biodiesel was announced as one of the major fields in 1999. Since 2004, the government has offered the biodiesel business the same preferential policies that they previously offered to the corn-based ethanol industry in order to support it. For every 3.785 L of biodiesel produced from waste oil and soybeans, the government offered a tax exemption of 1 USD. In India, a developing nation comparable to China, the government has established National Missions on Biofuels to promote the Jatropha-based biodiesel industry. Nearly 0.34 billion USD have been invested in Jatropha planting bases, and various purchasing policies, such as preferential tax and concessional loan policies, have been implemented (Xu et al. 2016).

Streamline permitting and regulation

Barriers to investing in this field can be removed by streamlining the permits and regulatory procedures involved with producing biodiesel from waste. Governments should develop precise rules and expedited processes for acquiring licenses, permits, and environmental approvals linked to the conversion of waste into biodiesel. This regulatory efficiency and clarity will make it easier to build biodiesel manufacturing plants, guaranteeing environmental compliance while reducing administrative expenses. In this regard, the European and American nations established regulatory measures earlier and have moved further in their efforts to promote biodiesel. For instance, as an example, in North America, the United States government offers grants and loan guarantees on a national scale through programs such as the Bioenergy Program for Advanced Biofuels and Biorefinery Assistance Program.

Additionally, blenders are granted an excise tax incentive of 1.00 USD per gallon of pure biodiesel blended with petroleum diesel. Similarly, operating incentives were given to successful registers who meet the program's requirements through the ecoENERGY for Biofuels Program. Through a combination of the National Biodiesel Production Program and Social Fuel Stamp, subsidies are offered in South America to benefit both biodiesel producers and family farmers in Brazil. Different degrees of tax incentives for biodiesel and biodiesel blending are offered throughout Europe. For instance, biodiesel blends are taxed more favorably in Finland than in eight other nations, which include Denmark, France, Sweden, and others. Finland taxes fuel based on its carbon dioxide concentration. To encourage the production of 8.42 billion liters of biodiesel in 2020, the Indonesian government gave (a 1.909 billion USD) subsidy, while Thailand eliminated import tariffs for B30 and above biodiesel (Zhu and Fan 2023).

Establishing clear environmental standards

Biofuel production is proposed to be combined with the treatment of nitrogen-rich municipal waste and carbon dioxide-containing flue gases to be deemed more sustainable and cost-effective (Osman et al. 2021b). Governments should develop clear and comprehensive environmental standards specific to biodiesel production from waste. These standards should address key environmental considerations, such as air emissions, wastewater management, and waste disposal. By establishing specific guidelines tailored to the characteristics of biodiesel production from waste, governments can ensure that environmental impacts are effectively mitigated while providing a level playing field for industry participants. Clear standards enable biodiesel producers to design their facilities and operations in compliance with environmental requirements from the outset.

Climate change concerns and energy transitions address not only energy technologies and innovations to decarbonize economies but also financial mechanisms to enable such transitions. The concepts of green finance and green investment have expanded in recent years, bringing perspectives to support sustainable projects. In Brazil, the biofuel policy (RenovaBio) established a carbon market called "Decarbonization Credits" (CBIOs), which is a financial instrument designed to incentivize the production and use of sustainable biofuels and reduce greenhouse gas emissions. The findings suggest that green finance needs to advance with a clear definition of their requirements and standards, not to fund non-green projects and projects that overlook social and environmental sustainability for economic benefits, and to enable investors to better assess the risks and opportunities of their investments. While some studies suggest that biofuels could play a role in the transition to a green economy, others warn of the environmental costs associated with large-scale products leading to negative impacts on biodiversity and land–water use. The green finance issue in Brazil will depend on sustainable agriculture practices and designing the RenovaBio program to be transparent, accountable, and socially and environmentally responsible. Green finance is essential for financing the energy transition towards renewable sources, as it considers renewable energy processes and reduces the financial burden. Brazil's energy sector emissions have increased significantly in 2021, with land-use change being the sector with the highest emissions. The country has made significant strides in promoting renewable energy and has implemented policies and programs to support the development of renewable energy. However, Brazil has faced challenges in establishing financing mechanisms for the energy transition, such as land use change, which affects land use, water resources, and pressure on water resources. In a study by Lazaro et al. (2023), green finance and investments focused on socio-environmental sustainability offer opportunities for Brazil in various sectors. This study examines the scientific literature on green finance and explores the obstacles and opportunities to establish a financial mechanism for green finance under the 2017 Brazilian Biofuels Policy. The Brazilian government supports the program as a market-based climate-energy policy and is expected to mobilize capital markets to support green projects (Lazaro et al. 2023).

Reduced global warming and promoting renewable and environmentally friendly fuels made from sustainable feedstock are both India's biofuel program goals. The nation has implemented several policies and programs to control the production and marketing of biofuels, including blending ethanol with petrol and biodiesel with diesel, rewarding the use of bio-based goods and fuels, and participating in clean energy initiatives. It is challenging to pass specific legislation to address the problems with the marketing of biofuels, nevertheless, because many regulations lack simple outreach among the general public and companies (Saravanan et al. 2018).

Biofuels are considered an option to reduce greenhouse gas emissions and increase energy supply diversity, security of supply, job creation, and rural development. However, various concerns have been expressed on various presumed negative environmental impacts. Global biofuel targets are likely to strongly impact land use and agricultural markets. New biofuel mandates, such as the Renewable Fuels Standard in the United States and the Renewable Energy Directive in the European Union, provide perspectives on the expanded demand for biofuels worldwide. In the European Union, the Directive 2009/28/EC on the promotion of the use of energy from renewable sources set mandatory targets of a 10% share of renewable energy in transport for 2020 in each European Union Member State, and a 6% reduction in greenhouse gas emissions from road transport fuels (Scarlat and Dallemand 2011).

Fostering research and development

Governments should allocate resources to support research and development initiatives focused on improving biodiesel production technologies, feedstock utilization, and refining processes. Collaborative research partnerships between academia, industry, and government institutions can drive innovation, enhance conversion efficiencies, and optimize the quality and performance of biodiesel from waste. Funding research programs and establishing innovation hubs will accelerate technological advancements and knowledge sharing within the biodiesel sector. The development of waste-based biodiesel production depends on fostering cooperation between research organizations, academic institutions, and business stakeholders. Governments should make it easier for research collaborations and networks to form, encouraging resource sharing and knowledge exchange. Synergistic improvements can result from collaborative efforts because they allow researchers to pool their knowledge, get access to specialized tools, and collectively address challenging research problems. Such partnerships could lead to innovations in waste-to-biodiesel conversion technologies. Governments should invest significant money in waste-based biodiesel research and development. Governments can assist the development of novel technology, catalysts, and processes that increase the productivity and cost-effectiveness of biodiesel production from trash by funding research projects that are essential first steps toward commercialization.

Developing waste collection infrastructure

Infrastructure refers to the various structures that underpin modern society, including networked systems that deliver services like energy, water, waste management, transport, and telecommunications. Social infrastructure includes social protection, healthcare, finance, insurance, education, law enforcement, and justice. These complex socio-technical systems are embedded within human systems and operate on behalf of society. The interplay between physical and social components creates the potential for lock-in, where long-lived assets shape future patterns of behavior and development. Infrastructure services are delivered by complex socio-technical networks, which economies of scale, public goods, and merit goods can characterize. Infrastructure systems have much in common with the Sustainable Development Goals (SDGs), and they are intimately intertwined. Infrastructure provides essential services to people, protects them from hazards, enables access to services, and participates in the economy. Unreliable infrastructure systems limit productivity, and costly infrastructure services add to production costs, undermining business competitiveness. Infrastructure enabling communication has diffuse benefits by widening product and labor markets and promoting innovation through exchanging ideas (Thacker et al. 2019).

Solid waste management is a crucial issue affecting the environment, economy, and society. Sustainable solid waste management practices are essential for meeting public health goals, environmental issues, resource value, and climate change. Uncollected and poorly disposed waste has significant health and environmental impacts, and addressing these impacts is often more expensive than developing and operating adequate waste management systems. Sharma et al. (2021) recommended strong policies prioritizing investments in the decentralization of solid waste systems, localization of supply chains, recycling and green recovery, information sharing, and international collaboration to achieve the United Nations Sustainable Development Goals (UN-SDGs).

The waste management sector aims to achieve a circular economy, particularly in the European Union and China, which promote a circular economy. This focuses on boosting reuse and reducing landfilling to maximize resources and extend their lifespan. However, developing and emerging economies face challenges in transitioning from open dumpsites to controlled landfills, particularly in developing countries with high urban population growth and economic expansion. Despite its higher environmental impact, landfilling remains the backbone of municipal solid waste management in these countries. Stakeholders in the waste management sector must be aware of the implications of landfilling and the benefits of implementing good practices to improve efficiency and environmental profile. Latin America and the Caribbean (LA&C) face similar challenges, with most countries struggling to eliminate dumpsters while transitioning to landfilling technologies. Waste management is a critical sector to focus on in developing countries, and it is essential to study and improve the sector from an environmental perspective with comprehensive proposals. Life cycle assessment (LCA) has become a critical tool for decision-making in developed countries, as different treatment methods may have different benefits (Margallo et al. 2019; Osman et al. 2021a).

Maiurova et al. (2022) discuss the potential of digitalization in waste management in Moscow, Russia, to mitigate climate change impacts on the environment and improve resource recovery. The article analyzes existing waste management facilities in Moscow and compares them to those in Berlin. Digitalization can minimize unrecycled municipal solid waste while conserving raw materials and reducing operational costs and greenhouse gas emissions. The study proposes a digitalization approach to accelerate societal transition through the waste recycling industry, aligning with the 2030 United Nations Agenda. The case study in Moscow and Berlin highlights the benefits of digitalization in waste management practices, such as reducing unemployment rates, maximizing pick-up time, and enhancing efficiency. The research also highlights the potential of a convolutional neural network-based identification system to reduce unrecycled waste volume by 20%. This approach could be replicated worldwide to resist resource consumption and deliver socio-economic and environmental benefits.

Mihai and Grozavu (2019) aimed to reveal the exposure of rural communities in the northeast region of Romania to illegal waste dumping practices due to poor waste collection schemes before rural dumpsite closure under European Union regulations. The study aimed to highlight the role of collection efficiency afterward in reducing this environmental threat, supported by activities promoting a rural circular economy framework. The objectives included identifying gaps between uncollected household waste and wild dumps, a multi-scale approach at county and rural municipality levels, calculating rural uncollected household waste at the county level, and promoting the 3, 6, or 9 Rs policy (reduce, reuse, repair, recovery, refurbish, repurpose, remanufacture, recycle, refuse) at household and community levels. The study argued that official statistics regarding uncontrolled waste disposal practices should be confronted with sound estimation methods of uncollected waste flow to better understand potential pollution issues and explain geographical disparities.

Achieving affordable clean energy under the Sustainable Development Goal (SDG 7) is challenging in Nigeria and other African nations. Most current energy strategies are either not sustainable or poorly maintained. Nigeria is a major exporter of fossil fuels but currently faces a serious energy crisis, necessitating the search for a sustainable, renewable form of energy as an alternative to fossil fuels. Biofuel has been identified as a sustainable form of renewable energy in Nigeria, with sugarcane, cassava, plant seed, and waste materials being possible feedstocks for bioethanol and biodiesel products. The use of waste materials and nonedible, underutilized seed oil, such as *Jatropha curcas* will help minimize the controversies associated with the use of food materials as feedstock for biofuel production in Nigeria and other nations in Africa (Adewuyi 2020).

Governments should invest in the development of waste collection infrastructure to encourage the production of biodiesel from waste. This includes establishing efficient collection systems, promoting waste segregation at the source, and incentivizing waste generators to separate and supply suitable feedstock for biodiesel production. Public–private partnerships can be formed to create collection networks, ensuring a steady and reliable supply of waste materials for biodiesel producers.

Raising awareness and promoting education

Raising public awareness about the benefits of biodiesel from waste is vital for its acceptance and adoption. Governments should implement educational campaigns to inform the public, businesses, and industries about biodiesel's environmental and economic advantages. Educational initiatives can also target waste management professionals, providing training and technical assistance on waste-to-biodiesel conversion processes. By fostering awareness and knowledge, governments can create a supportive environment for biodiesel production from waste.

In this context, improperly disposing of domestically produced used cooking oil is a significant environmental and social issue. InnovOleum, a social reverse logistics system, aims to collect and recycle used cooking oil through schools. The system provides funds from the sale of collected used cooking oils to invest in environmental education, green infrastructure, and technology. To date, over 200,000 Euros have been distributed to participating schools for this purpose. This innovative approach can significantly contribute to the bioeconomy and the environment by reducing waste and promoting sustainable practices. The biofuel industry is also benefiting from the recycling of used cooking oil, which is a valuable resource for biodiesel production (Loizides et al. 2019).

Fostering international cooperation

International cooperation and knowledge sharing are crucial for developing the biodiesel industry. Governments should encourage collaboration between countries, sharing best practices, policies, and experiences related to biodiesel production from waste. Governments can foster technology transfer through international partnerships, promote trade in biodiesel products, and work together towards global sustainability goals. International cooperation in several areas will be required to create a sustainable global biofuel sector. The best practices for growing sustainable feedstock need to be promoted to areas lacking resources to adhere to sustainability certification programs and access international markets. Joint research and development activities are required to generate biofuel conversion processes to ensure capacity growth and knowledge transfer. Developing countries must participate in the technological development process to efficiently deploy advanced biofuels. Cooperation between developed and developing countries, as well as between developed and developing countries, is required. Initiatives backed by the government should encourage vertical and horizontal access to technology and skills for sustainable biofuel production. Promoting international collaboration in developing sustainability standards and coordinating certification programs for biofuels and biomass products is critical for assuring marketability and long-term production. This will boost global biofuel commerce and promote trade in biofuels and feedstocks. Global convergence of technical standards, including fuel and vehicle norms, will aid in integrating infrastructure and consumer adoption. Sharing experiences between developing markets and large biofuel-producing nations will enable the seamless entry of biofuels into new markets. Several global groups, like the International Energy Agency (IEA) Bioenergy Implementing Agreement 28 and Task 39, are working to produce sustainable bioenergy and biofuels (Kumar et al. 2023c).

In conclusion, encouraging biodiesel production from waste requires a comprehensive and supportive policy framework. By implementing the policy recommendations outlined above, governments can drive market growth, stimulate investment, and accelerate the transition to a sustainable and resilient energy future. The promotion of biodiesel from waste not only reduces greenhouse gas emissions and waste accumulation, enhances energy security and fosters economic development. With robust policies in place, biodiesel from waste can significantly mitigate climate change, promote circular economy practices, and create a more sustainable world for future generations.

Conclusion

In conclusion, the global energy crisis, environmental pollution, and health issues associated with the extensive reliance on oil-based products necessitate the exploration of alternative fuels. Biodiesel, derived from waste materials, emerges as a promising renewable, biodegradable, and nontoxic fuel option. This comprehensive review sheds light on its advantages, challenges, and potential for a sustainable future. Throughout the review, various waste materials have been explored as viable feedstocks for biodiesel production. These materials include waste cooking oil, animal fats, vegetable oil, algae, fish waste, municipal solid waste, and sewage sludge. By diversifying feedstock sources, biodiesel production becomes more sustainable and less reliant on traditional agriculture-based feedstocks. Waste-based biodiesel presents a renewable and environmentally friendly solution to conventional diesel fuel, significantly reducing greenhouse gas emissions and playing a vital role in mitigating climate change. By utilizing readily biodegradable and renewable feedstocks, biodiesel promotes sustainable waste management practices, effectively converting waste resources into valuable energy sources. This innovative approach not only helps reduce dependence on finite fossil fuels but also contributes to a more sustainable and circular economy. With its potential to address both energy and waste management challenges, waste-based biodiesel emerges as a crucial contributor to a greener future. To unlock the full potential of biodiesel production, researchers turned to the power of computational chemistry. Through this cutting-edge field, they gained invaluable insights into the complex chemical reactions involved in the production process. Computational chemistry techniques enabled them to understand reaction mechanisms, kinetics, and catalyst design, thereby optimizing process parameters and improving efficiency. Additionally, machine learning and data mining techniques further enhanced biodiesel production by providing precise predictions and optimizing various production parameters. By identifying key factors influencing biodiesel production, these advanced approaches significantly enhanced overall process efficiency. The integration of machine learning and data mining in biodiesel production from waste resources yielded promising results. It not only boosted yield but also optimized the entire production process. The review article emphasized how waste-based biodiesel production contributed to waste management, reduced emissions, economic stability, energy diversification, and climate change mitigation. These benefits became even more significant when considering the projected increase in greenhouse gas emissions by 50% by 2050. It became clear that biodiesel had the potential to replace 7% of the world's fossil fuels by 2030, underlining the importance of this sustainable fuel option. However, technological advancements alone were not enough. The manuscript stressed the vital role of policy recommendations in promoting the widespread adoption of waste-based biodiesel production. Supportive policies that promote the utilization of waste materials and sustainable practices are essential for achieving environmental sustainability. By creating a favorable regulatory framework and providing incentives for investment and research, policymakers can drive the transition to a more sustainable and greener energy sector. These policy measures will not only enable the efficient utilization of waste resources but also contribute to reducing greenhouse gas emissions and fostering a more sustainable future.

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Declarations

AIO declares that he is Editor of Environmental Chemistry Letters.

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