

Chapter

The Use of Non-Food Biomass for Biodiesel Production: Technological and Environmental Challenges [Part 1]

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Abstract

The urgent global transition towards renewable energy has positioned biodiesel as a pivotal alternative for decarbonizing industrial sector. Moving beyond the contentious “food-versus-fuel” dilemma of first-generation biofuels, this review focuses on the sustainable production of biodiesel from non-food biomass, including agricultural residues, non-edible oilseed crops (e.g., *Jatropha curcas* and *Pongamia pinnata*), waste streams, and microalgae. The chapter provides a systematic analysis of the entire value chain, beginning with a classification of biofuel generations and a critique of food-based feedstocks’ socio-economic and environmental limitations. It then details the typology of advanced non-food feedstocks and the technological evolution in conversion processes, highlighting breakthroughs in heterogeneous catalysis and microwave-assisted and ultrasonic transesterification that enhance efficiency and sustainability. The analysis further addresses critical technological and environmental challenges, such as feedstock variability and emission profiles.

Keywords: biodiesel, non-food biomass, transesterification, heterogeneous catalysis, circular economy, sustainability

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the imperative to mitigate climate change and enhance energy security. This shift is accelerating the development of sustainable alternatives to fossil fuels, with biodiesel emerging as a critically important solution for decarbonizing the transportation sector [1]. Unlike conventional diesel, biodiesel derived from non-food biomass offers significant environmental advantages, including substantial lifecycle greenhouse gas emission reductions, while strategically avoiding competition with global food

supplies [2–8]. The biofuel industry has evolved through distinct generations, each aiming to overcome the limitations of its predecessor. First-generation biofuels, produced from edible crops like corn, sugarcane, and vegetable oils, ignited a widespread debate over the “food-versus-fuel” dilemma, raising concerns over food security, land-use change, and ultimately, their net carbon benefit. This has catalyzed a pivotal re-evaluation, propelling the industry towards more sustainable feedstocks. Second-generation biofuels derived from lignocellulosic biomass and third-generation fuels from algae and photosynthetic microorganisms represent a more sustainable pathway by utilizing non-food resources, agricultural and forestry residues, and waste streams [4]. This chapter comprehensively explores the frontier of non-food biodiesel. It begins by establishing the conceptual framework, defining biofuel generations, and outlining biodiesel’s role within the broader global energy transition. It then critically examines the socio-economic and environmental limitations of food-based feedstocks, building a compelling case for the necessity of non-food alternatives. The core of the chapter provides a detailed typology of non-food biomass—from resilient energy crops like *Jatropha* and *Pongamia* to waste cooking oils and algal species—and delves into the technological advancements revolutionizing their conversion into biodiesel. This includes a critical analysis of the evolution from homogeneous to heterogeneous catalytic systems and the application of process intensification technologies like microwave and ultrasound. Finally, the chapter addresses the persistent technological and environmental challenges, such as feedstock variability and NO_x emissions that must be overcome for widespread commercialization. By synthesizing the current state of knowledge and technology, this review aims to provide a holistic understanding of the opportunities and hurdles in non-food biodiesel production, charting a path for its integration as a sustainable and equitable component of the future energy system.

2. Conceptual framework and global issues

2.1 Definition and classification of biofuels (first, second, and third generations)

Biofuels are liquid or gaseous fuels derived from biomass, such as agricultural crops including corn, sugarcane, rapeseed, and sunflower, and represent a renewable alternative to fossil fuels [9]. They are typically classified into three generations based on the feedstock and conversion processes involved (**Figure 1**). First-generation biofuels are produced from food crops like corn, sugarcane, and vegetable oils, yielding bioethanol and biodiesel through fermentation and transesterification [10–17]. However, the use of biofuel, instead of minimizing gas emission, it contributes to several environmental and societal problems. A global agricultural model reveals that corn-based ethanol nearly doubles greenhouse gas emissions over 30 years rather than achieving the expected 20% reduction. Similarly, switchgrass biofuels grown on U.S. corn lands raise emissions by 50% due to land-use changes [17]. Furthermore, diverting large portions of crops to fuel production raises concerns over food security and price volatility [13, 14]. Policies are evolving to address these concerns: the European Union has capped first-generation biofuels at 7% of transportation energy consumption to limit land-use impacts. Similarly, the U.S. Renewable Fuel Standard has shifted focus towards advanced biofuels derived from non-food sources, moving away from conventional corn-based ethanol to reduce environmental drawbacks [18–20]. Despite these challenges, first-generation biofuels may maintain relevance

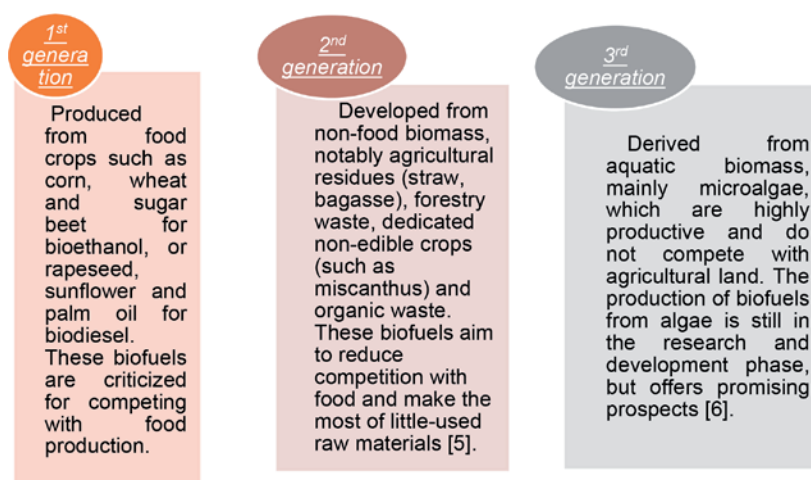


Figure 1.
 Evolution of biofuel generations: feedstocks and characteristics.

in specific applications through enhanced catalytic conversion technologies that improve efficiency, integration into combined food-energy production systems that optimize land use, and strategic utilization of agricultural residues and waste materials rather than dedicated food crops [21–24]. Second-generation biofuels attempt to overcome food-versus-fuel and environmental challenges by utilizing lignocellulosic biomass such as agricultural residues, forestry waste, and energy crops [25, 26]. These feedstocks avoid direct competition with food production while providing opportunities for waste valorization. Lifecycle analyses suggest lower GHG emissions than fossil fuels due to carbon sequestration during growth [27]. Yet, commercialization remains difficult because lignocellulosic biomass is structurally resistant, necessitating costly pretreatments like steam explosion or acid hydrolysis [28]. Progress has been achieved through innovations in nanostructured enzymes and bifunctional catalysts [29]. While enzymatic hydrolysis and fermentation dominate current approaches, thermochemical methods such as pyrolysis and gasification show promise for diverse feedstocks [30]. Successful projects in Brazil, using sugarcane bagasse [31], and in Sweden, with forestry residues, demonstrate the importance of supportive policy frameworks [32]. Third-generation biofuels, derived from algae and photosynthetic microorganisms, represent a more sustainable alternative by avoiding food crop competition and requiring less arable land [33–36]. Algae can be cultivated in freshwater, seawater, or wastewater, achieving high productivity while absorbing carbon dioxide [37–39]. Their primary limitation lies in high production costs, driven by cultivation, harvesting, and processing complexities [40–43]. Advances in metabolic engineering, synthetic biology, and nanotechnology are being explored to enhance efficiency, strain performance, and energy return [44]. Despite challenges, algae-based fuels promise significant GHG reductions with minimal impact on food systems or land use, provided research and development efforts continue [45, 46].

2.2 The global energy context and biodiesel role in the energy transition

The global energy landscape is undergoing a profound transformation, driven by technological advancements, policy shifts, and growing environmental concerns.

According to the International Energy Agency (IEA) World Energy Outlook 2023, demand for traditional fossil fuels—coal, oil, and natural gas—is projected to peak before 2030 under the Stated Policies Scenario (STEPS). This anticipated milestone represents a major departure from over a century of fossil fuel dominance, during which these sources consistently supplied about 80% of global energy needs [47], highlighting the world's gradual but decisive shift towards diversified, low-carbon energy systems. Within this transition, biodiesel is emerging as a viable and strategically important alternative fuel, particularly for decarbonizing the transportation sector, which remains one of the largest contributors to global CO₂ emissions. Road transport alone accounts for a substantial portion of fossil fuel consumption, making it a prime target for emission reduction strategies. Research indicates that even a modest 10% increase in biodiesel's share of transport fuels could significantly slow the growth rate of CO₂ emissions from road vehicles. This positions biodiesel not merely as a supplementary fuel, but as an immediately deployable mitigation tool in the global effort to meet climate targets. The environmental performance of biodiesel, however, is highly dependent on the choice of feedstock. For instance, life cycle assessment (LCA) studies on rapeseed biodiesel generally report substantial reductions in greenhouse gas (GHG) emissions compared with conventional fossil diesel. However, the extent of these emission savings varies considerably depending on factors such as agricultural practices, fertilizer application, crop yield, and the energy intensity of biodiesel production and processing stages [48, 49]. This wide range of reported values indicates that the environmental performance of rapeseed biodiesel is highly dependent on how the feedstock is cultivated and converted. These results underscore the critical importance of feedstock selection and management in maximizing the environmental advantages of biodiesel. In addition, sustainability assessments should not be limited to emission reductions alone, but should also account for broader impacts, including land-use changes, soil and water resource management, and potential ecological consequences. Therefore, ensuring that biodiesel feedstocks are sourced from environmentally responsible and socially equitable supply chains is essential for biodiesel to effectively contribute to long-term clean energy and decarbonization strategies.

2.3 Limitations of food-based feedstocks and the case for non-food biomass

The production of first-generation biofuel, derived from food crops such as corn, sugarcane, soybean, and palm oil, has sparked significant debate due to its social, environmental, and economic implications. One of the most prominent concerns is the competition between fuel and food production. Diverting staple crops to fuel manufacturing can limit their availability for human consumption and livestock feed, driving up global food prices. Such price increases disproportionately affect low-income populations, particularly in developing nations where food expenditures account for a large share of household income [50]. Beyond economic impacts, the rising demand for biofuel feedstocks has contributed to large-scale land acquisitions, or “land grabbing,” especially in parts of Africa, Asia, and Latin America. These transactions often involve foreign investors or corporations acquiring vast tracts of land for biofuel crop cultivation, displacing local farmers and indigenous communities. The result is not only the loss of livelihoods but also cultural disruption and increased social tensions [51]. Environmental drawbacks are also substantial. Expansion of agricultural land to meet biofuel feedstock demand has driven deforestation, habitat loss, and ecosystem degradation. Land-use change

releases large amounts of stored carbon dioxide, potentially offsetting the climate benefits of biofuels. In countries like Indonesia and Brazil, clearing forests or draining peatlands for oil palm or sugarcane plantations has become a major source of GHG emissions [51].

Intensive monoculture farming associated with these crops also consumes significant water resources and relies heavily on fertilizers and pesticides, which can degrade soil quality, contaminate water supplies, and reduce long-term agricultural sustainability. Recognizing these limitations, many governments and international bodies have reassessed their biofuel strategies. Some have introduced caps or phase-out timelines for first-generation biofuels, while others are actively promoting alternatives with lower environmental and social risks. This has accelerated interest in non-food biomass as the foundation for second-generation biofuels. Such feedstocks include agricultural residues (e.g., straw, corn stover), forestry residues, organic municipal waste, and non-edible energy crops (**Figure 2**) [52]. Second-generation biofuels offer several advantages: they reduce competition for arable land, make use of abundant lignocellulosic materials that are otherwise underutilized, and enable the valorization of waste streams. Converting residues and organic waste into fuel not only reduces reliance on food crops but also supports circular economy principles by minimizing landfill use and lowering methane emissions from decomposition. Nonetheless, technical and economic barriers persist. Processing lignocellulosic biomass requires complex pretreatment to break down the rigid structure of plant cell walls, followed by enzymatic hydrolysis and fermentation. These steps can be costly and energy-intensive. However, advances in biotechnology, catalyst design, and process engineering are gradually improving conversion yields and reducing costs. With sustained research and development, the transition from food-based to non-food feedstocks could become both commercially viable and environmentally superior, reinforcing the role of biofuels as a sustainable component of the global energy transition.

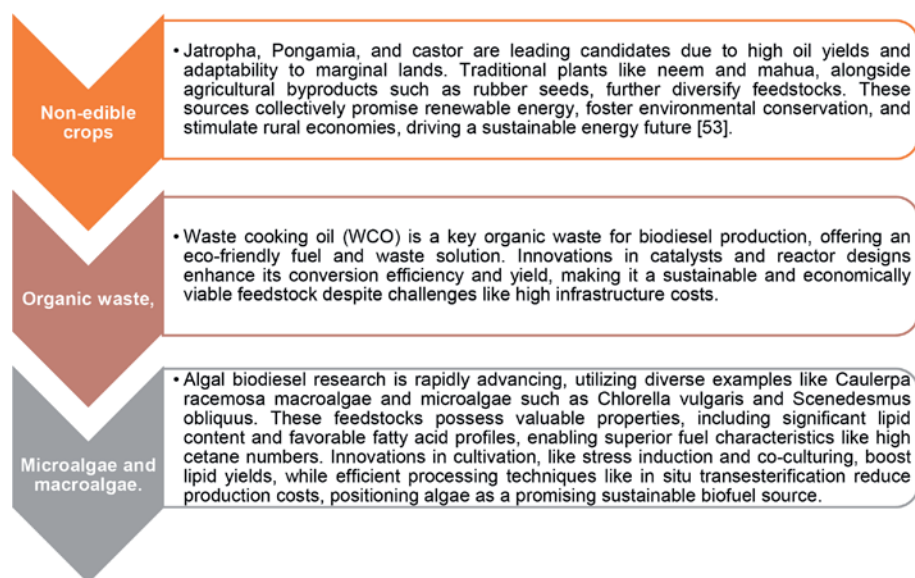


Figure 2.
Typology of non-food biomass.

3. Typology of non-food biomass

The systematic classification of non-food feedstocks for biodiesel production is a critical step in advancing sustainable bioenergy systems, particularly in the context of global energy transitions. Such classification enables a clearer understanding of feedstock availability, conversion potential, and environmental performance, while helping to minimize competition with food resources and reduce associated socio-economic and ecological impacts. These renewable resources are typically categorized into three groups: non-edible crops, organic waste, and microalgae/macroalgae (**Figure 2**). Each category presents distinct opportunities and challenges across the biofuel value chain. Rising global demand for renewable energy has stimulated interest in non-edible crops, which avoid competition with food resources. Unlike edible oils such as soybean or palm oil, these crops can yield substantial oil without compromising food security. Many non-edible crops are well-suited to marginal lands, requiring minimal water and fertilizers, enhancing both their economic viability and environmental sustainability [53]. Their oils contain fatty acids suitable for transesterification, producing biodiesel with properties comparable to conventional diesel. Non-edible biodiesel also reduces greenhouse gas emissions and enhances energy independence. Research continues to optimize oil extraction, engine performance, and cost efficiency, positioning non-edible crops as key players in the future of clean energy. These crops have gained attention as sustainable feedstocks, offering an eco-friendly alternative to conventional diesel without competing with food production. For example, *Jatropha curcas* (**Figure 3**) is particularly promising due to its high oil content and ability to thrive in arid conditions with minimal inputs [54]. Similarly, *Pongamia pinnata* provides comparable oil yields while improving soil fertility through natural nitrogen fixation (**Figure 3**) [55]. Castor plants offer high oil content but require careful handling due to toxic compounds. Traditional resources such as neem and mahua remain important where naturally abundant. Agricultural byproducts, like rubber seeds, also represent viable biodiesel sources. Collectively, these non-edible feedstocks support renewable energy production on marginal lands, promote

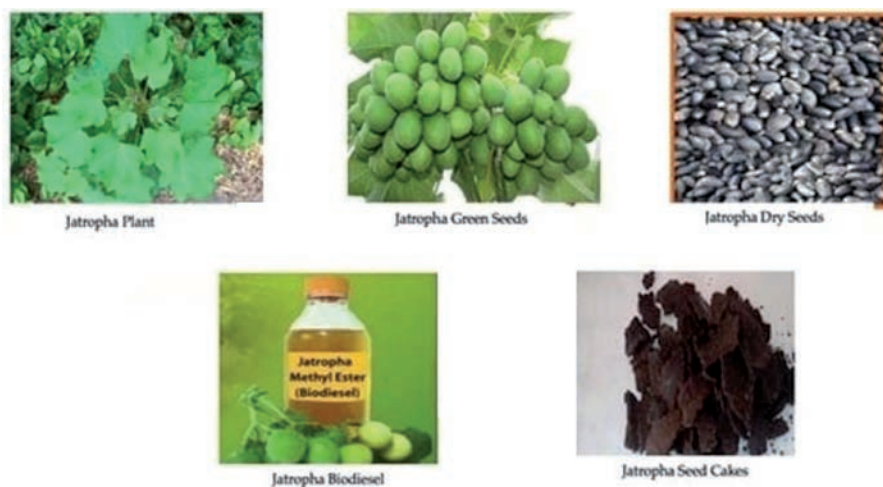


Figure 3.
Jatropha as a non-edible feedstock for biodiesel production [54].

environmental conservation, enhance energy independence, and create economic opportunities in rural areas. Their continued development mitigates reliance on fossil fuels and reduces the food-versus-fuel dilemma. *Jatropha curcas*, in particular, offers 27–40% oil content, tolerance to marginal lands, and no competition with food crops [54–58]. The plant's oil can be converted through transesterification into biodiesel meeting standard fuel specifications and international EN and ASTM standards [59]. Key advantages include its substantial oil yield, non-edible status that preserves food security, and capacity to grow in poor soil conditions with minimal water requirements [60–63]. Environmentally, *Jatropha* cultivation offers carbon sequestration benefits while reclaiming degraded lands [64–66]. However, challenges persist including high production costs from labor-intensive harvesting, seed toxicity requiring careful handling, and variable yields impacting economic viability [67–69]. Recent technological advances are addressing these limitations through improved transesterification processes using novel catalysts [70]. The crop demonstrates significant socioeconomic potential by creating rural employment opportunities and enhancing energy security, particularly in developing regions [71, 72]. Recent studies demonstrate that biodiesel derived from *Pongamia pinnata*, offers a viable alternative to fossil diesel, balancing engine performance with environmental benefits [73–79]. For example, Gaur and Goyal found that a 20% blend of mixed biodiesel (waste cooking oil and *Pongamia* oil) reduced CO and HC emissions by 30% while maintaining engine compatibility, though NO_x emissions increased due to higher oxygen content [73]. Similarly, Mulla and Shah reported that *Pongamia* biodiesel produced via CaO nanocatalysts achieved 95% yield, with B20 blends showing a 5.7% increase in indicated power (**Figure 4**) [74]. Biocatalysts, such as banana waste-derived nanocatalysts, further optimized transesterification, yielding 96.3% biodiesel from *Jatropha*-*Pongamia* blends in just 10 minutes [75]. Dolomite-based catalysts also proved effective for *Pongamia*, achieving 92.3% yield while supporting afforestation and SDGs [76]. Coating engines with thermal barriers improved combustion efficiency for *Pongamia*-*Azadirachta* blends, reducing HC and CO emissions but increasing NO_x by 9% [77]. Statistically optimized *Pongamia* biodiesel met ASTM standards, with a 78.3% yield under mild reaction



Figure 4.
Pongamia tree flowering 1.5 years after planting in a trial plot in Buntoi, PulangPisau, Central Kalimantan [55].

conditions (55°C, 60 minutes) [78]. Lemongrass oil (LGO) has emerged as a promising non-edible biodiesel feedstock, demonstrating competitive engine performance and emission characteristics compared to conventional diesel (**Figure 5**) [79]. Experimental studies on 3.5–5.2 kW diesel engines reveal that LGO blends (10–30% v/v) achieve brake thermal efficiency (BTE) comparable to diesel (LG20 $\approx$ diesel) but exhibit higher specific fuel consumption (SFC) due to lower calorific value [80]. Emission analyses show significant reductions in nitrogen and carbon oxides [80–82], attributed to LGO's oxygenated combustion and lower peak flame temperatures. Advanced formulations, such as LGO biodiesel with dibutyl ether additive, further optimize performance at compression ratio 17.5, reducing CO, CO₂, and NO_x while maintaining mechanical efficiency [83]. Recent studies have explored novel approaches that incorporate bio-based multi-wall carbon nanotubes into lemongrass oil (LGO) emulsions, revealing multiple performance enhancements. Specifically, this addition has been shown to significantly reduce the ignition delay by 17.6% and shorten the overall combustion duration by 18.5% [84]. These improvements are primarily attributed to the superior thermal conductivity of additive, which promotes more efficient heat transfer within the fuel droplets, leading to faster vaporization, improved atomization, and more complete combustion. Consequently, integrating BMWCNTs into LGO emulsions not only enhances combustion efficiency but may also contribute to reduced pollutant formation and better engine performance.

Another promising non-edible biodiesel source is neem (*Azadirachta indica*) oil, which contains 30–40% oil in its seeds and can be converted to biodiesel through transesterification [85, 86]. Optimizing reaction parameters, such as temperature, methanol-to-oil ratio, and catalyst concentration, is crucial to achieving high biodiesel yield [86]. The resulting neem biodiesel exhibits fuel properties, including density, kinematic viscosity, and calorific value, that comply with ASTM standards, making it suitable for diesel engines [87, 88]. Studies on biodiesel blends enhanced with alumina nanoparticles demonstrate improved combustion efficiency and reduced emissions of CO, HC, and particulate matter [89]. Machine learning models have been applied to predict engine performance and emission behavior with high accuracy, reinforcing the feasibility of neem biodiesel as a sustainable fuel [89]. Additionally, neem butyl ester produced via acid-catalyzed transesterification has shown comparable performance and emission characteristics to conventional diesel in compression ignition engines [90]. Furthermore, the use of organic waste-derived feedstocks, such as waste cooking oil, provides an eco-friendly and low-cost



Figure 5. Lemongrass plant (A), lemongrass oil (B), and lemongrass stalks (C) [79].

alternative for biodiesel production, aligning with circular economy principles [89, 91]. Contemporary research has significantly advanced waste cooking oil (WCO) biodiesel production through innovative reactor designs and catalytic processes. Jarungwongsathien et al. demonstrated the efficacy of a rotating tube reactor (RTR) system, achieving 89.72% biodiesel yield in just 11.23 minutes while reducing free fatty acid (FFA) content from 6 to 1.89% - with economic analysis showing a remarkably short 3.1-year payback period due to reduced operating costs [92]. Catalyst development has been particularly transformative, as shown by Alahmar et al. who engineered a bifunctional Ce/Mn/ γ -Al₂O₃ catalyst that attained 97% conversion of high-FFA WCO through simultaneous esterification and transesterification, leveraging its high basicity (1.543 mmol/g) and surface area (143 m²/g) [93]. Further innovations in nanocatalysts include Rezaeifar et al.'s α -Fe₂O₃/CuO composite RSM optimization showed the methanol/WCO ratio was the most impactful variable yielding a 94.27% biodiesel yield under optimal conditions. The catalyst exhibited strong reusability, demonstrating its potential as an effective heterogeneous catalyst [94]. Green chemistry approaches have also emerged, with Sahu et al. synthesized a heterogeneous CaO nanocatalyst using watermelon peel extract for the transesterification of soybean oil into biodiesel. Optimal conditions (20:1 methanol:oil ratio, 8% catalyst, 2.5 h at 65°C) resulted in a high biodiesel yield [95]. Selvam et al. evaluated pentanol-blended WCO-biodiesel. The B30+ blend demonstrated superior performance compared to pure diesel, improving combustion (higher heat release and pressure). Crucially, this blend achieved substantial reductions in CO (31.75%), HC (20.28%), and NO (14.82%) compared to other biodiesel blends, proving it to be a sustainable and highly efficient automotive fuel [96]. The integration of artificial intelligence has further optimized performance parameters, as Biberici et al. investigation utilized artificial neural network (ANN) and Response Surface Methodology models to predict and optimize the performance and exhaust emissions of a diesel engine fueled by a blend of diesel and waste oil biodiesel. The RSM model achieved high accuracy successfully maximizing brake thermal efficiency (BTE) while minimizing consumption and emissions. Optimal engine operation was achieved at an injection pressure of 180 bar and 100 percent biodiesel ratio, demonstrating that the combined use of RSM, ANN, and advanced algorithms offers a highly accurate optimization framework [97]. Comparative feedstock analyses by Liew et al. using non-edible oils such as soapnut seed kernel oil (SKO) and used cooking oil were studied [98]. SKO was extracted via Soxhlet at varying durations and characterized for pH, density, and acid number. Transesterification produced biodiesel, with SKO outperforming UCO, showing suitable pH (6.5), density (780 kg/m³), and acid number (2.43 mg KOH/g) [98].

However, infrastructure costs, particularly for bio-refineries, remain a major barrier to large-scale biodiesel production. Innovative feedstock strategies, such as integrating waste cooking oil with microalgae, have shown promise in enhancing process efficiency and reducing overall production costs [99, 100]. Dejene demonstrated that hybrid biodiesel feedstocks combining microalgae and WCO can achieve high conversion efficiencies while maintaining desirable fuel properties, suggesting a feasible approach for sustainable biodiesel supply chains [100]. These collective advancements position WCO biodiesel as a technically mature alternative, though challenges persist in NO_x mitigation, cold flow properties, and scaling heterogeneous catalyst production [92–99]. Recent studies demonstrate significant progress in algal biodiesel production through innovative cultivation and processing techniques [100]. Aboueldahab et al. [101] analyzes eight Red Sea seaweed

species for biodiesel potential. Seasonal biochemical analysis revealed significant variations in lipids, carbohydrates, and proteins. *Caulerpa racemosa* was the most promising, with high, consistent lipid yields (up to 12.76% CDW) and a favorable fatty acid profile rich in saturated fats like palmitic acid. Predictive models indicated excellent fuel properties, including high cetane numbers and suitable cold-flow characteristics, confirming the seaweed's strong potential as a sustainable biodiesel source [101]. For microalgae, the comparison of *Chlorella vulgaris* biodiesel proves that the in situ transesterification reduced capital costs by 31% (\$3.48 M vs. \$5.05 M) and achieved a shorter payback period (1.72 years) compared to solvent extraction [102]. Engine performance studies reveal promising results: Allasi et al. showed *Scenedesmus obliquus* biodiesel with 20% n-butanol additive improved brake thermal efficiency while reducing CO and hydrocarbon emissions though NO_x increased due to higher combustion temperatures [103]. Supply chain optimization is critical for scalability, as demonstrated by Panwar et al., whose genetic algorithm model reduced costs by prioritizing facility placement and utilizing mixed feedstocks (macroalgae/WCO), though production facilities [104]. Life cycle assessments by Liu et al. revealed wastewater-cultivated microalgae reduced environmental impacts by 52% compared to freshwater systems, with carbon sequestration potential during cultivation offsetting 69.8% of supply chain emissions [105].

Sun et al. [106] tested *Dunaliella salina* microalgae biodiesel blends (DSB10-DSB30) in a diesel engine. Brake thermal efficiency was highest for pure diesel (DSB0), but biodiesel blends showed better performance between 2000 and 2500 rpm due to higher oxygen content, enhancing combustion. However, specific fuel consumption increased with biodiesel concentration. Emissions analysis revealed lower CO but higher CO₂ and NO_x for biodiesel blends, particularly at higher speeds due to increased combustion temperatures [106]. Advanced cultivation techniques further improve yields. Poh et al. [107] investigated post-harvest stress on *Chlorella vulgaris* to increase lipid content for biodiesel. Applying one day of nutrient starvation combined with salinity (6.0 g/L) in darkness achieved the highest lipid yield of 38.8–40.28% by dry weight. The extracted lipids contained suitable fatty acids (linoleic, linolenic, and palmitic acid), similar to conventional vegetable oils, confirming their viability as a biodiesel feedstock [107]. Co-culture systems offer additional gains. By combining *Chlorella pyrenoidosa* and *Cutaneotrichosporonoleaginosum*, Wu et al. [108] achieved a lipid concentration of 18.15 g/L and a lipid productivity of 4.03 g/L/day. The system enabled pH self-regulation and nutrient synergism, scaling effectively even with cassava starch hydrolysate and demonstrating pH self-regulation and nutrient synergism [108].

4. Technologies for converting non-food biomass into biodiesel

The shift from fossil fuels to renewable energy has accelerated the development of technologies for converting non-food biomass into biodiesel. While the core chemical process of transesterification remains constant, the methods of its execution have evolved significantly to address the limitations of traditional approaches and improve overall sustainability and economic viability. This evolution has led to the development of advanced processes utilizing heterogeneous catalysts, microwave, and ultrasonic technologies, each offering distinct advantages over the classic use of homogeneous catalysts. Historically, homogeneous

catalysts, such as sodium hydroxide and potassium hydroxide, have been the standard for biodiesel production. These catalysts dissolve completely in the reaction mixture, ensuring excellent contact with the reactants and leading to fast reaction rates and high conversion yields. However, this method has significant drawbacks. The main challenge lies in the complex and energy-intensive downstream processing required to separate the catalyst and purify the biodiesel. This typically involves multiple washing steps, which not only consume a lot of energy but also generate a large volume of contaminated wastewater, creating environmental and disposal challenges. Furthermore, since these catalysts cannot be recovered and reused, the process becomes less economically and environmentally sustainable in the long run. The limitations of homogeneous catalysts led to a strong push for heterogeneous catalysts. These are solid catalysts that do not dissolve in the reaction mixture, which simplifies the separation process immensely. They can be easily removed by filtration or centrifugation and, most importantly, can be reused, reducing operational costs and waste generation. This reusability also facilitates continuous-flow production systems, making the technology more scalable for industrial applications. Recent research has yielded remarkable results with heterogeneous catalysts [109–124]. For example, Santoso et al. [111] optimized biodiesel synthesis from waste cooking oil using a $\text{Na}_2\text{O}/\gamma\text{-Al}_2\text{O}_3$ catalyst and ultrasonic assistance. The best yield (83.51%) was achieved with a 3% catalyst loading, a 12:1 methanol-to-oil molar ratio, at 65°C for 15 minutes. The main biodiesel components identified were methyl elaidate, methyl palmitate, and methyl linoleate. The catalyst's crystal size was 30.59 nm, and the process successfully reduced free fatty acids for efficient transesterification [111]. The development of green synthesis methods has also emerged, with researchers successfully creating calcium oxide (CaO) nanoparticles from waste orange peel extract to achieve a 93.4% biodiesel yield from WCO [113]. Other notable examples include a nano-magnetic $\text{CaO}/\text{Fe}_2\text{O}_3/\text{feldspar}$ catalyst that provides high yields from various wild plant seed oils, with the added benefit of easy magnetic separation and reusability [118]. A significant breakthrough is the creation of catalysts, like hierarchical porous $\gamma\text{-Al}_2\text{O}_3$ modified with MoV metal oxides, that can perform simultaneous esterification and transesterification in a single step, which simplifies the process and enhances cost-effectiveness [123]. Microwave-assisted transesterification is essential for process efficiency. Unlike conventional heating, which heats from the outside in, microwaves directly and rapidly heat the polar molecules in the reaction mixture. This targeted and instantaneous heating dramatically accelerates reaction kinetics, reducing reaction times from hours to mere minutes [124]. This technology offers improved energy efficiency by minimizing heat loss. It is particularly effective for in situ transesterification of microalgae, as it combines oil extraction and conversion into a single step, which is ideal for large-scale, sustainable biofuel production. The use of ultrasonic waves is another powerful method of process intensification. Ultrasound operates on the principle of acoustic cavitation, where sound waves create and collapse microscopic bubbles in the liquid. This violent collapse generates localized high temperatures and pressures, effectively breaking down the immiscible oil and alcohol phases and significantly enhancing mass transfer between the reactants. This physical action leads to a considerable increase in reaction rate and efficiency. Studies have shown that ultrasonic-assisted transesterification can achieve high yields while also reducing energy consumption by up to 85% compared to conventional methods [125–128].

5. Technological and environmental challenges

Feedstock variability poses a dual challenge and opportunity for the widespread adoption of biodiesel derived from non-food biomass. Unlike petroleum, a relatively uniform raw material, non-food biomass is a diverse and inconsistent collection of materials, including dedicated oilseed crops, agricultural residues, and organic wastes. This variability is a defining characteristic of the bioenergy sector, impacting every stage of production from collection and pretreatment to the final quality of the biodiesel. The primary challenge stems from compositional differences, such as variations in oil content, fatty acid profiles, and impurity levels (e.g., free fatty acids and moisture) across different feedstocks. These variations can be influenced by species, growing conditions, and storage duration. For example, a feedstock with a high free fatty acid content may require a two-step transesterification process to prevent soap formation, whereas a different feedstock with lower FFA levels might be processed using a single step [129]. This lack of uniformity in feedstock composition directly hinders the standardization of conversion processes. A process optimized for a specific type of biomass may be inefficient or fail when applied to another, leading to increased capital and operational costs. Facilities must be flexible enough to handle various feedstocks, requiring more related to feedstock variability in biodiesel production.

6. Summary of key points

This chapter [part 1] highlights for the critical biodiesel production role in transitioning towards a sustainable energy future. The findings presented across various sections of this paper demonstrate that non-food feedstocks—including dedicated crops, agricultural wastes, and algae—offer a compelling solution to the “food-versus-fuel” dilemma, while simultaneously providing a pathway for waste valorization. Technological advancements in transesterification have been instrumental in this progress. The shift from classic, environmentally problematic homogeneous catalysts to more efficient and sustainable heterogeneous catalysts has significantly improved biodiesel yields and simplified purification processes. Modern techniques like microwave and ultrasonic assisted transesterification further intensify these processes, drastically reducing reaction times and energy consumption. These innovations, combined with the strategic application of artificial intelligence and advanced modeling, are making non-food biodiesel a technically viable alternative to fossil fuels. However, several key challenges remain that must be addressed for widespread adoption. The variability in feedstock composition requires flexible and robust processing technologies to ensure consistent biodiesel quality. The economics of production are heavily dependent on optimizing the entire value chain, from feedstock sourcing and collection to the valorization of co-products in an integrated biorefinery model. Furthermore, the environmental impacts of biodiesel must be continuously evaluated using life cycle assessments to ensure that benefits such as reduced greenhouse gas emissions are not offset by negative effects like increased NO_x emissions or unsustainable land use. Finally, the logistical and infrastructural challenges of building a new supply chain for a diverse set of biomass feedstocks remain a significant hurdle. In summary, the transition to non-food biodiesel is a complex but necessary journey. With continued research and development focused on innovative catalysts, efficient processing technologies, and integrated, circular-economy-based supply chains,

non-food biodiesel is well-positioned to become a cornerstone of the global energy transition, providing a renewable, cleaner, and more sustainable fuel for the future.

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Conflict of interest

The authors declared no conflicts of interest.

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References

- [1] Capgemini. Biofuels: Potential, applications, and challenges. 2024. Available from: <https://www.capgemini.com/insights/expert-perspectives/biofuels-potential-applications-and-challenges/> [Accessed: May 13, 2025]
- [2] Parameswaran B, Gnansounou E, Raveendran S, Pandey A. Enzymes for second generation biofuels: Recent developments and future perspectives. *Bioresource Technology Reports*. 2018;5:52-61. DOI: 10.1016/j.biteb.2018.06.005
- [3] Biofuels Offer Hope for Hard-to-Decarbonise Sectors. *The Australian*. Available from: <https://www.theaustralian.com.au/business/mining-energy/biofuels-offer-hope-for-hardtodecarbonise-sectors/news-story/81c37a6602760947a29e6c7d72c91bb1>; [Accessed: May 13, 2025]
- [4] Cultures Sciences Chimie. Les biocarburants : de la 1ère à la 3ème génération. Disponible sur: <https://culturesciences.chimie.ens.fr/thematiques/chimie-organique/catalyse/les-biocarburants-de-la-1ere-a-la-3eme-generation> [Consulted: Mai 13, 2025]
- [5] Ministère de l'Agriculture. Tout savoir sur les biocarburants. Disponible sur: <https://agriculture.gouv.fr/tout-savoir-sur-les-biocarburants> [Consulted: Mai 13, 2025]
- [6] Ecosources. Les biocarburants de troisième génération. Disponible sur: <https://www.ecosources.org/biocarburant-de-troisieme-generation> [Consulted: Mai 13, 2025]
- [7] Deshmukh A. Technical and economical feasibility of biofuels for engine applications. In: *SAE Technical Paper 2009-24-0087*. Warrendale (PA): Society of Automotive Engineers; 2009. DOI: 10.4271/2009-24-0087
- [8] Vilas Bôas RN, Mendes MF. A review of biodiesel production from non-edible raw materials using the transesterification process with a focus on influence of feedstock composition and free fatty acids. *Journal of the Chilean Chemical Society*. 2022;67(1):5433-5444. DOI: 10.4067/S0717-97072022000105433
- [9] Makarevičienė V, Gaidė I, Sendžikienė E. Heterogeneous catalysts from food waste for biodiesel synthesis—A comprehensive review. *Catalysts*. 2025;15(10):957. DOI: 10.3390/catal15100957
- [10] Wengenmayr R. *Renewable Energy: Sustainable Concepts for the Energy Change*. 2nd ed. Weinheim: Wiley-VCH; 2013
- [11] Adessi A, De Philippis R. Biodiesel from microalgae. In: Hallenbeck PC, editor. *Microbial Technologies in Advanced Biofuels Production*. Springer; 2012. DOI: 10.1007/978-1-4614-1208-3_4
- [12] Mahapatra S, Kumar D, Singh B, Sachan PK. Biofuels and their sources of production: A review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus. *Energy Nexus*. 2021;4:100036. DOI: 10.1016/j.nexus.2021.100036
- [13] Nowack KF. Biofuels today and tomorrow. *Hydrocarbon Process*. 2007;86(2):87-95
- [14] Ackrill R, Kay A. Biofuels policy challenges. In: Ackrill R, Kay A,

editors. *The Growth of Biofuels in the 21st Century, Energy, climate and the environment series*. London: Palgrave Macmillan; 2014. pp. 180-217. DOI: 10.1057/9781137307897_9

[15] Haque SM, Bhat AH, Khan I. Biomass: An ageless raw material for biofuels. In: Kaur GH, Khan I, Bhat AH, editors. *Agricultural Biomass Based Potential Materials*. Springer; 2015. pp. 442-466. DOI: 10.1007/978-3-319-13847-3_20

[16] Zhang Y, Dube MA, McLean DD, Kates M. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. *Bioresource Technology*. 2003;**90**(3):229-240. DOI: 10.1016/s0960-8524(03)00150-0

[17] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*. 2008;**319**(5867):1238-1240. DOI: 10.1126/science.1151861

[18] European Commission. *Renewable Energy – Recast to 2030 (RED II)*. EU Science Hub; 2018. Available from: https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

[19] US Environmental Protection Agency. *Overview of the Renewable Fuel Standard Program*. EPA; 2025. Available from: <https://www.epa.gov/renewable-fuel-standard-program/program-overview-renewable-fuel-standard-program>

[20] US Environmental Protection Agency. *Final Renewable Fuels Standards Rule for 2023, 2024, and 2025*. EPA; 2023. Available from: <https://www.epa.gov>

[gov/renewable-fuel-standard/final-renewable-fuels-standards-rule-2023-2024-and-2025](https://www.epa.gov/renewable-fuel-standard/final-renewable-fuels-standards-rule-2023-2024-and-2025)

[21] Baskar G, Aiswarya R. Trends in catalytic production of biodiesel from various feedstocks. *Renewable and Sustainable Energy Reviews*. 2016;**57**:496-504. DOI: 10.1016/j.rser.2015.12.101

[22] Rezaei R, Mohadesi M, Moradi GR. Optimization of biodiesel production using waste mussel shell catalyst. *Fuel*. 2013;**109**:534-541. DOI: 10.1016/j.fuel.2013.03.004

[23] Yaghi M, Chidiac S, Awad S, El Rayess Y, Zgheib N. An overview of biodiesel production via heterogeneous catalysts: Synthesis, current advances, and challenges. *Clean Technologies*. 2025;**7**(3):62. DOI: 10.3390/cleantechnol7030062

[24] Meriatna HH, Riza M, Faisal M, Ahmadi S. Biodiesel production using waste banana peel as renewable base catalyst. *Materials Today Proceedings*. 2023;**87**(Pt. 2):214-217. DOI: 10.1016/j.matpr.2023.02.400

[25] Lee RA, Lavoie JM. From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Animal Frontiers*. 2013;**3**(2):6-11. DOI: 10.2527/af.2013-0010

[26] Kowalski Z, Kulczycka J, Verhé R, Desender L, De Clercq G, Makara A, et al. Second-generation biofuel production from the organic fraction of municipal solid waste. *Frontiers in Energy Research*. 2022;**25**:919415. DOI: 10.3389/fenrg.2022.919415

[27] Pramanik A, Sinha A, Chaubey KK, Hariharan S, Dayal D, Bachheti RK, et al. Second-generation bio-fuels:

Strategies for employing degraded land for climate change mitigation meeting united nation-sustainable development goals. *Sustainability*. 2023;**15**(9):7578. DOI: 10.3390/su15097578

[28] Figueiredo M, Mendes F. Problems found in the adaptation of a fluid cracking catalytic pilot plant for studying second generation biofuel production by pyrolysis. *Chemical Engineering Transactions*. 2012;**29**:691-696. DOI: 10.3303/CET1229116

[29] Jintao H, MuhdNoor ND, Kamarudin NHA, Ali MSM. Review of enzyme catalysis in sustainable biofuel production: A comparative study of waste oils and alternative feedstocks. *International Journal of Green Energy*. 2025;**22**(1):1-15

[30] Tagade A, Kirti N, Sawarkar AN. Pyrolysis of agricultural crop residues: An overview of researches by Indian scientific community. *Bioresource Technology Reports*. 2021;**15**:100761. DOI: 10.1016/j.biteb.2021.100761

[31] Rossi LM, Gallo JMR, Mattoso LHC, Buckeridge MS, Licence P, Allen DT. Ethanol from sugarcane and the Brazilian biomass-based energy and chemicals sector. *ACS Sustainable Chemistry & Engineering*. 2021;**9**(12):4293-4295. DOI: 10.1021/acssuschemeng.1c01678

[32] Yacout DMM, Tysklind M, Upadhyayula VKK. Socio-economic implications of forest-based biofuels for marine transportation in the Arctic: Sweden as a case study. *Frontiers in Climate*. 2024;**6**:1414813. DOI: 10.3389/fclim.2024.1414813

[33] Alam F, Mobin S, Chowdhury H. Third generation biofuel from algae. *Procedia Engineering*. 2015;**105**:763-768. DOI: 10.1016/j.proeng.2015.05.068

[34] Behera S, Singh R, Arora R, Sharma NK, Shukla M, Kumar S. Scope of algae as third generation biofuels. *Frontiers in Bioengineering and Biotechnology*. 2015;**2**:90. DOI: 10.3389/fbioe.2014.00090

[35] Dragone G, Fernandes BD, Vicente AA, Teixeira JA. Third generation biofuels from microalgae. In: Méndez-Vilas A, editor. *Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology*. 2010. pp. 1355-1366

[36] Lackner M, Köpke M. Third-generation biofuels: Bacteria and algae for better yield and sustainability. In: Lackner M, Sajjadi B, Chen W-Y, editors. *Handbook of Climate Change Mitigation and Adaptation*. 3rd ed. Springer; 2025. pp. 2411-2466. DOI: 10.1007/978-3-031-84483-6_90

[37] Li G, Yao J. A review of algae-based carbon capture, utilization, and storage (algae-based CCUS). *Gases*. 2024;**4**(4):376-398. DOI: 10.3390/gases4040024

[38] Tang Y. Algae used in achieving carbon neutrality by treating wastewater. *International Journal of Energy*. 2025;**8**(1):61-66. DOI: 10.54097/v8tjht95

[39] Hoque MM, Iannelli V, Padula F, Radice RP, Saha BK, Martelli G, et al. Microalgae: Green engines for achieving carbon sequestration, circular economy, and environmental sustainability—A review based on last ten years of research. *Bioengineering*. 2025;**12**(9):909. DOI: 10.3390/bioengineering12090909

[40] Veal MW, Caffrey KR, Chinn MS, Grunden AM. *Algae for Biofuels – Economic and Environmental Costs*. SRAC Publication No. 4310. Southern Regional Aquaculture Center, Mississippi

State University; 2013. Available from: <https://srac.msstate.edu/pdfs/Fact%20Sheets/4310%20Algae%20for%20Biofuels-%20Economic%20and%20Environmental%20Costs.pdf>

[41] Hannon M, Gimpel J, Tran M, Rasala B, Mayfield S. Biofuels from algae: Challenges and potential. *Biofuels*. 2010;**1**(5):763-784. DOI: 10.4155/bfs.10.44

[42] Adeniyi OM, Azimov U, Burluka A. Algae biofuel: Current status and future applications. *Renewable and Sustainable Energy Reviews*. 2018;**90**:316-335. DOI: 10.1016/j.rser.2018.03.067

[43] Papagianni S, Capellán-Pérez I, Adam A, Pastor A. Review and meta-analysis of energy return on investment and environmental indicators of biofuels. *Renewable and Sustainable Energy Reviews*. 2024;**203**:114737. DOI: 10.1016/j.rser.2024.114737

[44] Rial RC. Biofuels versus climate change: Exploring potentials and challenges in the energy transition. *Renewable and Sustainable Energy Reviews*. 2024;**196**:114369. DOI: 10.1016/j.rser.2024.114369

[45] Kant G, Hasan A, Yadav P, Pandey A, Srivastava S. The generational shift in biofuels: A path toward sustainable energy solutions. *Biomass and Bioenergy*. 2025;**196**:107757. DOI: 10.1016/j.biombioe.2025.107757

[46] Chowdhury R, Caetano N, Franchetti MJ, Hariprasad K. Life cycle based GHG emissions from algae based bioenergy with a special emphasis on climate change indicators and their uses in dynamic LCA: A review. *Sustainability*. 2023;**15**(3):1767. DOI: 10.3390/su15031767

[47] International Energy Agency. *World Energy Outlook 2023*. Paris: IEA; 2023. DOI: 10.1787/827374a6-en

[48] Yang X, Liu Y, Bezama A, Thrän D. Two birds with one stone: A combined environmental and economic performance assessment of rapeseed-based biodiesel production. *GCB Bioenergy*. 2022;**14**(2):215-241. DOI: 10.1111/gcbb.12913

[49] Gupta R, McRoberts R, Yu Z, Smith C, Sloan W, You S. Life cycle assessment of biodiesel production from rapeseed oil: Influence of process parameters and scale. *Bioresource Technology*. 2022;**360**:127532. DOI: 10.1016/j.biortech.2022.127532

[50] Fletcher RJ Jr, Robertson BA, Evans J, Doran PJ, Alavalapati JRR, Schemske DW. The impacts of biofuel crops on local biodiversity: A global synthesis. *Biodiversity and Conservation*. 2021;**30**(10):2863-2883

[51] Abreu M, Silva L, Ribeiro B, Ferreira A, Alves L, Paixão SM, et al. Low indirect land use change (ILUC) energy crops to bioenergy and biofuels—A review. *Energies*. 2022;**15**(12):4348. DOI: 10.3390/en15124348

[52] Antizar-Ladislao B, Turrion-Gomez JL. Second-generation biofuels and local bioenergy systems. *Biofuels Bioproducts Biorefining*. 2008;**2**(5):455-469. DOI: 10.1002/bbb.97

[53] Winberg J, Ekroos J, Eklundh L, Smith HG. Constraints on the availability of marginal land for bioenergy production in southern Sweden. *Biomass and Bioenergy*. 2024;**190**:107421. DOI: 10.1016/j.biombioe.2024.107421

[54] Neupane D, Bhattarai D, Ahmed Z, Das B, Pandey S, Solomon JKQ, et al. Growing *Jatropha* (*Jatropha curcas* L.) as a potential second-generation biodiesel feedstock. *Inventions*. 2021;**6**(4):60. DOI: 10.3390/inventions6040060

- [55] Leksono B, Rahman SA, Larjavaara M, Purbaya DA, Arpiwi NL, Samsudin YB, et al. Pongamia: A possible option for degraded land restoration and bioenergy production in Indonesia. *Forests*. 2021;**12**(11):1468. DOI: 10.3390/f12111468
- [56] Ruatpuia JVL, Halder G, Vanlalchhandama M, Lalsangpuui F, Boddula R, Al-Qahtani N, et al. *Jatropha curcas* oil as a potential feedstock for biodiesel production: A critical review. *Fuel*. 2024;**370**:131829. DOI: 10.1016/j.fuel.2024.131829
- [57] Yusuf NNAN, Kamarudin SK, Yaakob Z. Overview on the production of biodiesel from *Jatropha curcas* L. by using heterogeneous catalysts. *Biofuels, Bioproducts and Biorefining*. 2012;**6**(3):319-334. DOI: 10.1002/bbb.345
- [58] Che Hamzah NH, Khairuddin N, Siddique BM, Hassan MA. Potential of *Jatropha curcas* L. as biodiesel feedstock in Malaysia: A concise review. *PRO*. 2020;**8**(7):786. DOI: 10.3390/pr8070786
- [59] Sakthivel R, Ramesh K, Purnachandran R, Mohamed SP. A review on the properties, performance and emission aspects of the third generation biodiesels. *Renewable and Sustainable Energy Reviews*. 2018;**82**:2970-2992. DOI: 10.1016/j.rser.2017.10.037
- [60] Rodrigues J, Miranda I, Furquim L, Gominho J, Vasconcelos M, Barradas G, et al. Storage stability of *Jatropha curcas* L. oil naturally rich in gamma-tocopherol. *Industrial Crops and Products*. 2015;**64**:188-193. DOI: 10.1016/j.indcrop.2014.10.048
- [61] Abou Kheira AA, Atta NMM. Response of *Jatropha curcas* L. to water deficits: Yield, water use efficiency and oilseed characteristics. *Biomass and Bioenergy*. 2009;**33**(10):1343-1350. DOI: 10.1016/j.biombioe.2008.05.015
- [62] Pérez-Vázquez A, Hernández-Salinas G, Ávila-Reséndiz C, Valdés-Rodríguez OA, Gallardo-López F, García-Pérez E, et al. Effect of the soil water content on *Jatropha* seedlings in a tropical climate. *International Agrophysics*. 2013;**27**(4):351-357. DOI: 10.2478/intag-2013-0004
- [63] Al-Busaidi A, Ahmed M, Chikara J. The impact of heat and water stress conditions on the growth of the biofuel plant *Jatropha curcas*. *International Journal of Environmental Studies*. 2012;**13**(1):273-288. DOI: 10.1080/00207233.2012.663204
- [64] Wani SP, Chander G, Sahrawat KL, Srinivasa Rao C, Raghvendra G, Susanna P, et al. Carbon sequestration and land rehabilitation through *Jatropha curcas* (L.) plantation in degraded lands. *Agriculture, Ecosystems and Environment*. 2012;**161**:112-120. DOI: 10.1016/j.agee.2012.07.028
- [65] Baumert S, Khamzina A, Vlek PLG. Soil organic carbon sequestration in *Jatropha curcas* systems in Burkina Faso. *Land Degradation and Development*. 2016;**27**(6):1814-1823. DOI: 10.1002/ldr.2310
- [66] Zhang Z, Li J, Wang Z, Liu H, Wei K. Estimating soil carbon sequestration of *Jatropha* for sustainable aviation fuel pathway. *Water, Air, and Soil Pollution*. 2024;**235**(1):47. DOI: 10.1007/s11270-023-06826-5
- [67] Segerstedt A, Robert J. Revising the potential of large-scale *Jatropha* oil production in Tanzania: An economic land evaluation assessment. *Energy Policy*. 2013;**57**:491-505. DOI: 10.1016/j.enpol.2013.02.023

- [68] Mehra KS, Singh S, Singh AK, Kharkwal H, Avikal S, et al. Performance, energy, emission and cost analysis of *Jatropha* (*Jatropha Curcas*) oil as a biofuel for compression ignition engine. *Materials Today Proceedings*. 2021;**43**(Part 1):348-354. DOI: 10.1016/j.matpr.2020.11.675
- [69] Liu Y, Zhu Z, Zhang R, Zhao X. Life cycle assessment and life cycle cost analysis of *Jatropha* biodiesel production in China. *Biomass Conversion and Biorefinery*. 2024;**14**(22):28635-28660
- [70] Shafi ME, Alsabi HA, Almasoudi SH, Mufti FAM, Alowaidi SA, Alaswad AA. Catalytic conversion of *Jatropha curcas* oil to biodiesel using mussel shell-derived catalyst: Characterization, stability, and comparative study. *Inorganics*. 2024;**12**(4):109. DOI: 10.3390/inorganics12040109
- [71] Yang L, Zhou J, Pan C, Tu Q, Wang G, Duan J, et al. Environmental, energy, and economic assessment of *Jatropha curcas* L. biodiesel production in China. *Journal of Cleaner Production*. 2024;**470**:143286. DOI: 10.1016/j.jclepro.2024.143286
- [72] Nahar K. *Jatropha curcas* L: A Potential 2G Energy Crop to Produce Biofuel in Bangladesh: Agronomy, Biotechnology, Biodiesel and Byproducts. Cham: Springer Nature Switzerland; 2025
- [73] Gaur RK, Goyal R. Performance, emission, combustion and economics analysis of CI engine fueled with mixed oil biodiesel blends from waste cooking oil and pongamia oil. *SN Applied Sciences*. 2025;**7**(6):365. DOI: 10.1007/s42452-025-07150-7
- [74] Mulla AA, Shah AP. Production and engine performance analysis of biodiesel from *Pongamia pinnata* using PTSA and CaO nanocatalysts. *Biomass and Bioenergy*. 2025;**195**:107714. DOI: 10.1016/j.biombioe.2024.107714
- [75] Basumatary SF, Das B, Brahma S, Basumatary S. Musa ABB (Kachkal) banana waste derived heterogeneous nanocatalyst for transesterification of binary oil mixture of *Jatropha curcas* and *Pongamia pinnata* to biodiesel. *Bioresource Technology Reports*. 2025;**29**:102018. DOI: 10.1016/j.biteb.2024.102018
- [76] Sudalai S, Devanesan MG, Arumugam A. Dolomite as a potential source of heterogeneous catalyst for biodiesel production from *Pongamia pinnata*. *Nature Environment and Pollution Technology*. 2024;**23**(4). DOI: 10.46488/NEPT.2024.v23i04.042
- [77] Suresh R, Ashwin R, Uppuluri K, MohanRaj T. Experimental investigation and operating characteristics of LHR engine using *Pongamia pinnata* and *Azadirachta indica* biodiesel blend with industrial waste additive. In: *SAE Technical Paper 2025-28-0039*. DOI: 10.4271/2025-28-0039
- [78] Ali M, Kashif M, Zaidi AA, Jamil R. Statistical optimization of biodiesel production from non-edible *Pongamia pinnata* oil. *Periodica Polytechnica Chemical Engineering*. 2024;**68**(3):419-427. DOI: 10.3311/PPch.36753
- [79] Kiani HS, Ali A, Zahra S, Hassan ZU, Kubra KT, Azam M, et al. Phytochemical composition and pharmacological potential of lemongrass (*Cymbopogon*) and impact on gut microbiota. *AppliedChem*. 2022;**2**(4):16. DOI: 10.3390/appliedchem2040016
- [80] Gangolu NR, Gopidesi RK, Anudeep IM. Effects of lemongrass oil as fuel in diesel engine. *INCAS*

BULLETIN. 2020;**12**(4):63-70.
DOI: 10.13111/2066-8201.2020.12.4.6

[81] Saravana Kumar M, Prabhakar M, Prakash S, Senthil J, Thiagarajan C. Experimental analysis of lemon grass biodiesel (LGB) with different exhaust gas recirculation. *Materials Today: Proceedings*. 2020;**33**(Pt. 1):876-880. DOI: 10.1016/j.matpr.2020.06.405

[82] Kumar P, Kumar D, Shankar R, Kumar S, Saini P, Kumar N. Effect of synthesized lemongrass biodiesel on the performance and emission characteristics of a CI engine. *Sustainable Energy Technologies and Assessments*. 2023;**57**:103221. DOI: 10.1016/j.seta.2023.103221

[83] Paramasivam P, Balasubramanian A, Adeleke AA, Ikubanni PP, Kumar S, Prakash C, et al. Exploring alternative fuel solutions: Lemon grass oil biodiesel blend with dibutyl ether additive for VCR diesel engines – An experimental analysis. *Scientific Reports*. 2024;**14**:20272

[84] Ooi JB, Kau CC, Manoharan DN, Wang X, Tran M-V, Hung YM. Effects of multi-walled carbon nanotubes on the combustion, performance, and emission characteristics of a single-cylinder diesel engine fueled with palm-oil biodiesel–diesel blend. *Energy*. 2023;**281**:128350. DOI: 10.1016/j.energy.2023.128350

[85] Ali MH, Mashud M, Rubel MR, Ahmad RH. Biodiesel from neem oil as an alternative fuel for diesel engine. *Procedia Engineering*. 2013;**56**:625-630. DOI: 10.1016/j.proeng.2013.03.169

[86] Dash SK, Elumalai PV, Ranjit PS, Das PK, Kumar R, Kumar S, et al. Experimental investigation on synthesis of biodiesel from non-edible neem seed oil: Production optimization and evaluation of fuel properties. *Materials*

Today Proceedings. 2021;**47**(10):2463-2466. DOI: 10.1016/j.matpr.2021.04.551

[87] Fadairo AA, Wong PK, Ip WF, Ahmadi Ghadikolaei M, Cai Z, Ng KW, et al. Impact of neem oil biodiesel blends on physical and chemical properties of particulate matter emitted from diesel engines. *Environmental Pollution*. 2024;**362**:124972. DOI: 10.1016/j.envpol.2024.124972

[88] Arslan M, Ayyub H, Jamshaid M, Arslan A, Kalam MA, Ahmad F. Production, performance and emission of biodiesel from a mixture of castor oil and neem oil. *RSC Advances*. 2025;**15**(42):35296-35311. DOI: 10.1039/d5ra04004c

[89] Aswathanarayan MS, Santhosh N, Venkataramana SH, Kumar KS, Kamangar S, Arabi AIA, et al. Prediction of performance and emission features of diesel engine using alumina nanoparticles with neem oil biodiesel based on advanced ML algorithms. *Scientific Reports*. 2025;**15**:12683. DOI: 10.1038/s41598-025-97092-2

[90] Rajak AK, Harikrishna M, Zeenath SF, Dalal S, Karuna SL, Rajesh K, et al. Transesterification of neem seed oil for environmentally friendly biolubricants: Promoting circular economy in industrial processes. *Biomass and Bioenergy*. 2025;**200**:108012. DOI: 10.1016/j.biombioe.2025.108012

[91] Suzihaque MUH, Alwi H, Ibrahim UK, Abdullah S, Haron N. Biodiesel production from waste cooking oil: A brief review. *Materials Today Proceedings*. 2022;**63**(S1):S490-S495. DOI: 10.1016/j.matpr.2022.04.527

[92] Jarungwongsathien A, Chanthon N, Ngaosuwan K, Kiatkittipong W, Wongsawaeng D, Mens W, et al.

Cost-effective and simple biodiesel production process from waste cooking oil using a rotating tube reactor: Kinetic study and techno-economic analysis. *Renewable Energy*. 2025;**255**:123729. DOI: 10.1016/j.renene.2025.123729

[93] Alahmar NM, Wan Azelee NI, Toemen S. Efficient biodiesel production from waste cooking oil using a bifunctional Ce/Mn/ γ -Al₂O₃ catalysts. *Scientific Reports*. 2025;**15**:352

[94] Rezaeifar A, Mansouri M, Maleki B. Incorporation of CuO on the α -Fe₂O₃ nanoparticles as a heterogeneous catalyst for conversion of waste cooking oil into biodiesel. *Scientific Reports*. 2025;**15**:7067

[95] Sahu S, Saikia K, Gurunathan B, Dhakshinamoorthy A, Rokhum SL. Green synthesis of CaO nanocatalyst using watermelon peels for biodiesel production. *Molecular Catalysis*. 2023;**547**:113342. DOI: 10.1016/j.mcat.2023.113342

[96] Selvam M, Pragadish N, Harish KA, Srinivasan RG, Devarajan Y, Kaliappan N. Investigating emission characteristics and combustion performance of a CRDI engine utilizing novel biodiesel derived from waste cooking oil and pentanol blends. *Scientific Reports*. 2025;**15**:14742

[97] Biberici MA, Çelik MB, Ozhuner E. Engine performance and emission optimization with waste cooking oil biodiesel/diesel blend using ANN and RSM techniques coupled with ACKTR-DE and HHO algorithms. *BMC Chemistry*. 2025;**19**(1):137. DOI: 10.1186/s13065-025-01512-3

[98] Liew OI, Razali NF, Mansur SA, Fauzi NA, Razak AHA, Abd Aziz MH, et al. Comparison of *Sapindus Mukorossi* (soapnut seed kernel oil) and used

cooking oil via transesterification to produce biodiesel in terms of conversion percentage. *ARAM*. 2025;**136**(1):1220. DOI: 10.37934/aram.136.1.1220

[99] Bhran AA. A comparative techno-economic analysis of waste cooking oils and chlorella microalgae for sustainable biodiesel production. *PRO*. 2025;**13**(11):3526. DOI: 10.3390/pr13113526

[100] Dejene B, Bezu A. Biodiesel from blended microalgae and waste cooking oils: Optimization, characterization, and fuel quality studies. *AIMS Energy*. 2024;**12**(2):408-438. DOI: 10.3934/energy.2024019

[101] Aboueldahab M, Wu Y, Alwaleed E, Twagirayezu G, Xia A, Saber H. Maximizing the biodiesel production efficiency from Red Sea macroalgae: A seasonal and multivariate approach. *Biomass and Bioenergy*. 2025;**201**:108050. DOI: 10.1016/j.biombioe.2025.108050

[102] Pandian PM, Mathew F, Muttu M, Perumalsamy M. Techno-economic analysis of biodiesel production from *Chlorella vulgaris* using different potential biorefinery approaches. *Bioenergy Research*. 2025;**18**(1):21. DOI: 10.1007/s12155-025-10823-1

[103] Allasi HL, Murugan S, Ananda HK, Vairavel D. Enhancing diesel engine performance and emissions with N-butanol enhanced biodiesel derived from *Scenedesmus obliquus* algae. *Scientific Reports*. 2025;**15**:12924. DOI: 10.1038/s41598-025-92369-y

[104] Panwar P, Singh AP, Chauhan A, Arora R. Optimization of a macro-algae-based biodiesel supply chain: A multi-objective approach. *Discover Sustainability*. 2025;**6**:248. DOI: 10.1007/s43621-025-01022-1

- [105] Liu Y, Xia R, Wang Y, Zhao Y, Ju M. Life-cycle environmental impact assessment of microalgae biodiesel derived from different processes. *Industrial Crops and Products*. 2025;**233**:121381. DOI: 10.1016/j.indcrop.2025.121381
- [106] Sun H, Devanesan S, Aljawdah HM, Rithika M, Jhanani GK. Utilization of the *Dunaliella salina* microalgae by transesterification process with NaOH as catalyst in diesel combustion. *Renewable Energy*. 2025;**250**:123344. DOI: 10.1016/j.renene.2025.123344
- [107] Poh ZL, Kadir WNA, Lam MK, Uemura Y, Suparmaniam U, Lim JW, et al. The effect of stress environment towards lipid accumulation in microalgae after harvesting. *Renewable Energy*. 2020;**157**:842-853. DOI: 10.1016/j.renene.2020.03.081
- [108] Wu B, Zhou W, Gong Z, Ran S, He M, Zhong T, et al. Co-culture of *Chlorella pyrenoidosa* and *Cutaneotrichosporon oleaginosum* with enhanced biomass, lipid yield, and lipid productivity for micro-biodiesel production. *Renewable Energy*. 2025;**250**:123369. DOI: 10.1016/j.renene.2025.123369
- [109] Al-Hamamre Z, Sandouqa A, Al-Saida B, Shawabkeh RA, Alnaief M. Biodiesel production from waste cooking oil using heterogeneous KNO₃/oil shale ash catalyst. *Renewable Energy*. 2023;**211**:470-483. DOI: 10.1016/j.renene.2023.05.025
- [110] Karthikeyan M, Sathish S, Soosai MR, Prabu D, Venkatesan D. Optimized production of biodiesel from used (waste) cooking oil by utilizing a heterogeneous catalyst, and its studies for sustainable development. *Fuel*. 2026;**403**:136091. DOI: 10.1016/j.fuel.2025.136091
- [111] Santoso A, Kusumah TN, Sumari S, Wijaya AR, Retnosari R, Rachman IB, et al. Synthesis of biodiesel from waste cooking oil using heterogeneous catalyst of Na₂O/ γ -Al₂O₃ assisted by ultrasonic wave. *AIMS Energy*. 2022;**10**(5):1059-1073. DOI: 10.3934/energy.2022049
- [112] Moumeni O, Djerad S, Bouranene S, Taghri M, Chakroun C. Production of biodiesel from waste cooking oils using manganese oxide MnO as a heterogeneous catalyst. *Biofuels*. DOI: 10.1080/17597269.2025.2544476
- [113] Garg R, Garg R, Eddy NO, Abdulraheem MI, Hazzan OO, Abdi G. Green synthesis of calcium oxide nanocatalyst and application in transesterification of waste cooking oil. *Bioresources and Bioprocessing*. 2025;**12**:52
- [114] Mishra R, Shu C-M, Gollakota ARK. Transformation of waste cooking oil into biodiesel in a microwave reactor using nickel-loaded graphitic biochar catalyst. *Fuel*. 2025;**397**:135369. DOI: 10.1016/j.fuel.2025.135369
- [115] Helmiyati H, Budiman Y, Abbas GH, Dini FW, Khalil M. Highly efficient synthesis of biodiesel catalyzed by a cellulose@hematite-zirconia nanocomposite. *Heliyon*. 2021;**7**(3):e06622. DOI: 10.1016/j.heliyon.2021.e06622
- [116] Gonzaga VE, Romero R, Gómez-Espinosa RM, Romero A, Martínez SL, Natividad R. Biodiesel production from waste cooking oil catalyzed by a bifunctional catalyst. *ACS Omega*. 2021;**6**(37):24092-24105. DOI: 10.1021/acsomega.1c03586
- [117] Dhinakaran G, Vijayakumar G, Suvaitha SP, Harichandran G, Venkatachalam K. Conversion of neem oil (*Azadirachta indica*) to biodiesel

over SBA-15 supported sulphated zirconia catalysts. *Catalysis Letters*. 2024;**154**:2124-2139

[118] Hanif M, Bhatti IA, Hanif MA, Rashid U, Moser BR, Hanif A, et al. Nano-magnetic CaO/Fe₂O₃/feldspar catalysts for the production of biodiesel from waste oils. *Catalysts*. 2023;**13**(6):998. DOI: 10.3390/catal13060998

[119] Swarna SR, Srikanth HV, Anitha R, Swamy MT, Divakara TR, Krishnamurthy KN, et al. Biodiesel synthesis from mixed non-edible oil feedstock using K₂CO₃ in NH₄OH catalyst mixture. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. 2023;**45**(3):6901-6917. DOI: 10.1080/15567036.2023.2216163

[120] Saad M, Siyo B, Alrakkad H. Preparation and characterization of biodiesel from waste cooking oils using heterogeneous catalyst (Cat. TS-7) based on natural zeolite. *Heliyon*. 2023;**9**(6):e15836. DOI: 10.1016/j.heliyon.2023.e15836

[121] Foroutan R, Foroughi M, Tutunchi A, Ramavandi B, Terrón D, Pazos M. Production of biodiesel from waste cooking oil and non-edible *Moringa oleifera* oil utilizing a CaO/CuFe₂O₄/LaTiO₃ perovskite@Na bifunctional heterogeneous nanocatalyst. *Journal of Environmental Chemical Engineering*. 2025;**13**(4):117261. DOI: 10.1016/j.jece.2025.117261

[122] Perumal G, Magendradass D, Munusamy R, Gopal S. Optimization and kinetic studies on novel Mg(HPW₁₂O₄₀)/SiO₂ mesoporous solid catalysts for biodiesel production from *Bauhinia variegata* seed oil. *Chemical Engineering Research and Design*. 2025;**218**:824-838. DOI: 10.1016/j.cherd.2025.05.029

[123] Hou S, Xie W. Exploring hierarchical porous γ -Al₂O₃ modified with MoV metal oxides used as a high-efficiency solid catalyst for sustainable biodiesel production from low-cost acidic oils. *Renewable Energy*. 2025;**250**:123303. DOI: 10.1016/j.renene.2025.123303

[124] Das S, Kaushik B, Chaudhury AP, Basumatary S, Pratap P, Mohan S, et al. Microwave-assisted biodiesel production from WCO using snail shell-derived CaO@coal fly ash: Optimization via RSM, cost analysis, kinetics, thermodynamics, and bibliometrics. *Renewable Energy*. 2025;**254**:123741. DOI: 10.1016/j.renene.2025.123741

[125] Wang Y, Hao X, Da X, Zheng X. Ultrasound-assisted dual-enzyme system for the preparation of fatty acid ethyl esters. *Catalysis Letters*. 2025;**155**:74

[126] Abulizi A, Bai H, Saierkejiang N, Okitsu K, Maihemuti M, Talifu D. Synthesis of biodiesel from waste cooking oil using a pulsed high-intensity ultrasound method. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 2025;**47**(1):9435-9447. DOI: 10.1080/15567036.2021.1948935

[127] Yasvanthrajan N, Sivakumar P, Muthukumar K, Thanabalan M, Arunagiri A. Ultrasound assisted lipase catalysed transesterification using waste cottonseed oil. *Journal of the Taiwan Institute of Chemical Engineers*. 2025;**177**:106076. DOI: 10.1016/j.jtice.2025.106076

[128] Garuma WB, Bedru TK, Gindaba GT, Jayakumar M, Edae IT, Meshesha BT, et al. Optimization and characterization of ultrasonically extracted oil from watermelon seeds using response surface methodology: A pathway to biodiesel and epoxy oil

production. Biomass Conversion and Biorefinery. 2025;**15**:23135-23153

[129] Photaworn S, Tongurai C, Kungsanant S. Process development of two-step esterification plus catalyst solution recycling on waste vegetable oil possessing high free fatty acid. Chemical Engineering and Processing. 2017;**118**:1-8. DOI: 10.1016/j.cep.2017.04.013