

Review

Sustainable Biodiesel Production in India from Non-Edible and Waste Feedstocks

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Abstract:

India faces significant energy security challenges because crude oil import dependence remains high while demand for diesel continues to grow. Biodiesel from non-edible and waste feedstocks offers a sustainable route that can contribute to national blending targets and reduce reliance on imported fossil fuels. This review examines the present status, feedstock landscape, opportunities, barriers, and future pathways for biodiesel production in India using non-edible oilseeds such as *Jatropha curcas*, *Pongamia pinnata* and *Madhuca indica*, along with waste-derived resources such as used cooking oil and animal tallow. Current biodiesel output in India remains far below the quantity required to achieve meaningful blending targets, despite a substantial theoretical resource base. Sectoral growth has been constrained by feedstock supply limitations, cost pressures, fragmented collection systems, and policy and institutional challenges. At the same time, biodiesel development offers opportunities in waste valorization, rural income generation, greenhouse-gas mitigation, and partial import substitution. The review discusses technical, economic, environmental and policy dimensions relevant to the Indian context and outlines practical strategies for scaling sustainable biodiesel systems.

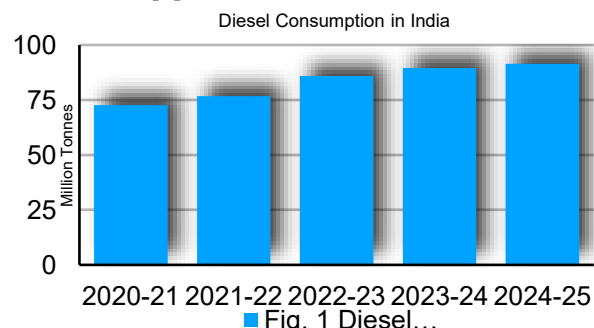
Keywords: biodiesel; India; non-edible oilseeds; used cooking oil; waste feedstocks; sustainable energy; biofuel policy.

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1. Introduction

India's transport and industrial sectors are highly reliable on diesel, and continued growth in fuel demand has intensified the country's energy security concerns. Heavy dependency on imported crude oil makes the economy vulnerable to price volatility and external supply risks, Figure 1 shows consumption of diesel in India. In this context, biodiesel has emerged as an attractive renewable alternatives because it can be produced from vegetable oils and fats and used in

compression-ignition engines with limited modification.[1]



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The significance of biodiesel in India extends beyond simple fuel substitution. It is also related to climate mitigation, waste management, rural development, and the broader objective of building a more resilient domestic energy system. Depending on feedstock and process conditions, biodiesel can reduce greenhouse-gas emissions and enhance biodegradability relative to petroleum diesel.[2]

The Indian biodiesel strategy mainly focused on non-edible and waste-based feedstocks rather than edible vegetable oils. This approach reduces direct competition with food uses and is particularly important in a country where edible oil imports are already substantial. Among the most studied non-edible feedstocks are Jatropha, Karanja, and Mahua, whereas used cooking oil and animal fats are the most visible waste-derived resources.[3][4]

Despite substantial interest, biodiesel deployment in India has progressed more slowly than originally expected. Production remains limited relative to national targets, and past experience has shown that optimistic assumptions about feedstock systems do not necessarily translate into commercial success. [3]A focused review is therefore necessary to evaluate the realistic prospects of biodiesel production in India from non-edible and waste feedstocks.

2. Current status of biodiesel in India

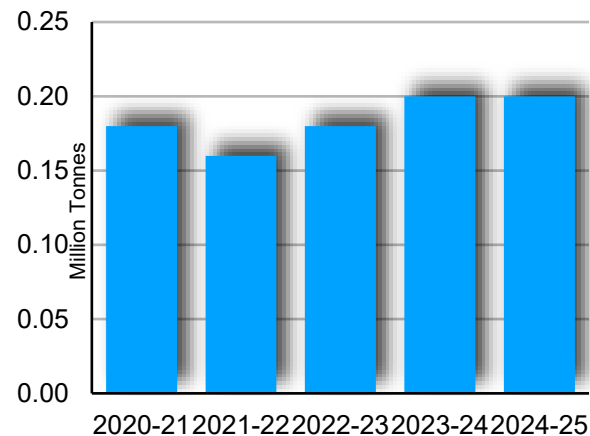
India's biodiesel sector can be described as strategically important but still underdeveloped in practical terms. Production has increased over time, yet total output remains small relative to the required quantity for modest blending targets.[5] Figure 2 shows biodiesel consumption detail in India. This gap indicates that the industry is still in an early stage of development rather than a mature deployment phase.

Installed biodiesel production capacity is considerably higher than actual output, but capacity utilization remains low because feedstock supply is irregular and procurement systems are not consistently reliable. Uncertainty in collection, pricing, transport and procurement continues to discourage large-scale investment and plant operation.[6] As a result, nominal

capacity and real production remain far apart in the Indian biodiesel economy.

Policy support for biodiesel has progressed over time. Early enthusiasm was strongly linked to the National Biodiesel Mission and to the idea that Jatropha could be widely cultivated on wastelands for low-cost biodiesel production. However, field experience showed that this approach did not achieve the expected scale, leading to a gradual shift toward more diversified feedstocks including Karanja, Mahua, used cooking oil and animal fats.[7]

Biodiesel Production in India



■ Fig 2. Biodiesel...

Oil marketing companies now play a visible role in biodiesel procurement and blending, but the national blending level remains low.[8] Although some progress has occurred, the pace remains insufficient to meet stated blending ambitions without major improvements in feedstock systems, economics and implementation capacity.

3. Non-edible oilseed feedstocks

3.1. General importance

Non-edible oilseed resources have long been considered important to India's biodiesel strategy because they offer the possibility of fuel production without direct competition with food crops. These feedstocks are especially relevant in India because edible oils are already in short supply and heavily imported. However, the success of non-edible oils depends less on theoretical oil yield and more on

realistic cultivation, collection, processing and marketing systems.

3.2. *Jatropha curcas*

Jatropha was initially promoted as an ideal biodiesel crop because of its non-edible oil content, assumed low-input character, and supposed adaptability to marginal lands. Policy narratives suggested that it could be cultivated widely on wastelands while still producing substantial quantities of oil-rich seeds.[9] Experience from India, however, showed that these expectations were often overstated under field conditions.

Farmer-level studies in southern India reported that many farmers abandoned *Jatropha* because yields were much lower than expected and economic returns were very less. In practice, the crop often required more water, management and care than originally claimed, particularly during establishment and fruiting phases. Weak planting material, uncertain market channels, limited extension support and lack of assured buyback arrangements further reduced farmer confidence.[10],[11]

The *Jatropha* experience remains important because it illustrates how biodiesel policy can underperform when agronomic assumptions are unrealistic and supply chains are not properly developed. Although *Jatropha* still has technical value as a non-edible oil source, it is no longer viewed as the single dominant solution for India's biodiesel future.

3.3. *Pongamia pinnata* (Karanja)

Karanja is widely regarded as one of the more promising non-edible biodiesel feedstocks for India. It is a leguminous tree species native to the Indian subcontinent and can grow under a range of climatic and soil conditions.[12] The seeds contain substantial oil, and the tree offers ecological co-benefits such as nitrogen fixation and suitability for degraded landscapes.[7]

From a biodiesel perspective, Karanja oil can be converted at good yield through transesterification, and the resulting fuel properties are generally compatible with biodiesel quality requirements. Because the oil is non-edible, there is no direct competition with food

use.[13] Karanja also fits better into long-term agroforestry and land restoration models than many annual crop systems.

Challenges remain, however, because Karanja trees require time to mature and collection systems for naturally occurring or semi-managed trees are not sufficiently organized in many regions. Even so, compared with *Jatropha*, Karanja is often seen as a more credible and locally adapted long-term option.

3.4. *Madhuca indica* (Mahua)

Mahua holds a distinctive place in the Indian biodiesel discussion because it combines technical feedstock potential with strong socio-economic importance in tribal and forest-fringe regions. Its seeds contain appreciable oil suitable for biodiesel production, while other parts of the tree are already integrated into existing livelihood systems. This gives Mahua both energy significance and local livelihood relevance.[14] Mahua oil can be converted effectively into biodiesel, although its relatively high free fatty acid content often requires pre-treatment or two-stage processing. Even with this added complexity, Mahua remains attractive because it is locally available in several states and can support decentralized rural value chains.[15] If properly organized, Mahua-based biodiesel systems can generate local income while supplying raw material for energy production.

The main challenge lies in improving collection, aggregation, storage and processing efficiency. Nevertheless, Mahua remains one of the most socio-economically relevant non-edible oilseed feedstocks in India.

3.5. Other non-edible oils

Other non-edible oils such as neem and kusum also appear in Indian biodiesel studies, although their role is generally secondary compared with *Jatropha*, Karanja and Mahua. These feedstocks may still contribute regionally or as part of blended raw-material systems where local availability exists.

4. Waste-based feedstocks

4.1. General importance of waste feedstocks

Waste-based feedstocks have become increasingly important because they support biodiesel production

without requiring additional agricultural land. They also align well with circular-economy principles by converting discarded oils and fats into useful energy carriers.[16] In India, the most important waste-derived biodiesel feedstocks are used cooking oil and animal fats or tallow.

Waste feedstocks may ultimately prove more scalable in the near term than plantation-based systems because they build on materials that already exist within urban and industrial metabolism. They also avoid many of the land-use and gestation-period issues associated with tree-based oilseed crops.[17] For these reasons, India's practical biodiesel future is increasingly linked to the success of organized waste oil and waste fat collection systems.

4.2. Used cooking oil

Used cooking oil has emerged as one of the most practical feedstocks for biodiesel production in India. Large quantities are generated from hotels, restaurants, food-processing units, canteens and households. Estimates suggest that national used cooking oil generation may be on the order of several million tonnes annually, indicating a substantial feedstock opportunity if effective collection systems are established.[18]

This feedstock is important not only for energy reasons but also because improper reuse of degraded cooking oil in the food chain raises public-health concerns.[19] The RUCO initiative promoted by the food safety authority encourages the collection and repurposing of used cooking oil for biodiesel rather than unsafe food reuse. This linkage between food-safety regulation and biofuel production represents one of the strongest practical foundations of India's current waste-based biodiesel strategy.[20]

Technically, used cooking oil can be converted effectively into biodiesel, although raw-material quality varies widely depending on source and cooking history. High free fatty acid content and impurities may necessitate pre-treatment before transesterification. Even with these requirements, used cooking oil often remains economically attractive because it is a waste resource rather than a cultivated feedstock.[21]

The main barrier is collection. Large bulk generators can be incorporated into formal systems relatively easily, but small decentralized food vendors are much harder to organize. Illegal diversion back into the informal food chain, uneven enforcement and insufficient aggregation networks continue to limit the quantity of used cooking oil reaching biodiesel plants.[22]

4.3. Animal fats and tallow

Animal fats and tallow are also viable biodiesel feedstocks. These materials arise as by-products from slaughterhouses and meat-processing operations and can be rendered into forms suitable for fuel conversion.[23] Their use supports waste valorization and can reduce disposal burdens associated with animal-processing residues.

Tallow-based biodiesel generally exhibits acceptable fuel properties, although cold-flow behavior and processing requirements depend on the exact composition of the feedstock.[24] In India, this feedstock has not scaled as strongly as used cooking oil, partly because rendering and collection systems are not uniformly organized and because animal fat also serves other industrial uses. Nevertheless, it remains an underutilized resource that can improve overall feedstock flexibility.[25]

5. Opportunities and benefits

The development of biodiesel from non-edible and waste feedstocks offers India economic, environmental, social and strategic benefits. These potential benefits explain why biodiesel continues to attract policy attention even though production remains relatively limited.[6] The current installed capacity for biodiesel processing in India is approximately 200,000 tonnes per year, though many units operate below capacity [26]. This underutilization can be attributed to several factors, including the high cost and inconsistent supply of suitable feedstocks, particularly given that feedstock accounts for 70–95% of total biodiesel production costs [27].

Economically, biodiesel can contribute to reducing dependence on imported petroleum products and can improve overall fuel diversification. Even partial

substitution of petroleum diesel with domestically produced biofuel can moderate import exposure and strengthen energy resilience. [28]The sector also creates employment opportunities across cultivation, collection, aggregation, transport, processing and plant operation, especially in rural and semi-urban regions. Non-edible oilseed-based biodiesel can support productive use of underutilized landscapes when cultivation is planned appropriately. Species such as Karanja can also contribute to ecological functions such as soil improvement and greening of degraded areas.[29] Mahua-based systems are particularly valuable because they combine energy potential with existing rural livelihood systems in parts of central India.[30]

Waste-based biodiesel offers additional benefits because it transforms problematic waste streams into useful resources. In the case of used cooking oil, biodiesel production also supports waste management and food safety by discouraging repeated use of degraded oil in food preparation. This gives the biodiesel pathway a public-health dimension in addition to its energy value.[16]

Environmentally, biodiesel can reduce life-cycle greenhouse-gas emissions compared with conventional diesel, especially when produced from waste feedstocks.[31] It can also lower the environmental burden associated with improper waste disposal and promote more circular resource use.[16] Depending on feedstock and processing pathway, biodiesel can contribute meaningfully to India's wider climate and sustainability goals.

Strategically, biodiesel supports national priorities related to energy security, waste valorization, rural development and lower-carbon growth. When linked with reliable local supply systems and predictable procurement arrangements, it can become part of a more diversified and resilient transport-fuel system.[32]

6. Barriers and challenges

Despite its promise, biodiesel production in India continues to face substantial barriers that limit scale and long-term viability. These challenges span the entire

value chain, from feedstock generation and collection to processing, procurement and blending.

Feedstock uncertainty is one of the most serious barriers. Plantation-based systems require long-term cultivation, survival, seed collection and aggregation, all of which depend on strong institutional coordination and farmer confidence.[33] The Jatropha experience showed that optimistic assumptions about yield, low-input cultivation and wasteland productivity can lead to disappointing outcomes.[34]

For non-edible oilseeds such as Karanja and Mahua, the issue is often less about technical possibility than about the absence of strong collection and market systems. Trees may exist across landscapes, but scattered availability, seasonality and weak aggregation reduce effective supply.[35] Without organized procurement networks, biodiesel plants cannot rely on a steady and economical raw-material flow. This challenge is further compounded by the instability of non-edible oils, which often necessitate extensive pretreatment, thereby increasing processing costs and diminishing their appeal to oil-producing companies [36].

Used cooking oil, although highly promising, faces its own supply-chain problems. Large quantities are generated, but only a limited share reaches the formal biodiesel chain because collection remains fragmented and enforcement is uneven. In some cases, used cooking oil is diverted back into the informal food chain, undermining both public health and biodiesel production.[19]

Economics is another major constraint. Biodiesel production costs remain sensitive to feedstock price, chemical inputs, transport and plant utilization rates. If supply is irregular, plants operate below capacity and unit costs increase further. Producers also need predictable prices and long-term offtake confidence to justify investment. The use of multiple suppliers and multiple feedstocks will require additional care in the characterization of each new batch of raw material and in monitoring of the products.

[37]

Technical quality issues are also important. Feedstocks with high free fatty acid content require more complex processing, and variable raw-material quality can affect

final fuel consistency. Inadequate quality control can create engine-performance concerns and reduce market confidence. Standardization and quality assurance are therefore essential for wider market growth.[16]

Policy and institutional gaps have further constrained the sector. While the policy direction is generally supportive, the pace of execution has often been slow. Procurement systems, local enforcement, feedstock mapping, extension support and infrastructure development have not always progressed in a coordinated manner. As a result, the broader biodiesel ecosystem remains incomplete.

7. Future pathways and recommendations

India's biodiesel sector is more likely to advance if future efforts move away from overly broad expectations and instead focus on realistic, feedstock-specific and regionally grounded strategies. The most important requirement is to build local reliable supply chains rather than relying on numerical targets alone.[38]

First, used cooking oil collection systems require major strengthening. Bulk food businesses should be systematically registered, traceability systems should be improved, and collection incentives should make formal disposal more attractive than diversion into informal channels.[19] Because used cooking oil is one of the most immediately available feedstocks in India, stronger implementation of collection and monitoring frameworks could yield relatively quick results.

Second, non-edible oilseed systems should be developed through organized local institutions rather than isolated plantation schemes. Farmer-producer organizations, cooperatives and decentralized aggregation networks can improve seed collection, transparency and feedstock reliability for species such as Karanja and Mahua. These systems are more likely to succeed when aligned with local ecological conditions and livelihood practices.[35]

Third, the economic framework for biodiesel needs to become more predictable. Producers need confidence that collected or processed biodiesel will be purchased at viable prices over a meaningful time horizon.[39] Long-term procurement mechanisms, viability support

and more stable price structures can improve investment attractiveness.

Fourth, technology and quality improvement should continue. Better catalysts, improved pre-treatment systems for high free fatty acid oils and small-scale decentralized processing technologies can reduce costs and widen the range of usable feedstocks.[40] At the same time, stronger quality assurance and adherence to fuel standards will be necessary to build buyer confidence.

Fifth, regional planning should guide deployment. Urban regions with high restaurant density are well suited for used cooking oil systems, whereas central and semi-arid regions may be better suited for Mahua- and Karanja-based value chains.[41] A differentiated strategy is likely to perform better than a single national model applied uniformly across all states.

Finally, biodiesel should be integrated into broader sustainability frameworks, including waste management, rural livelihoods, circular-economy policy and lower-carbon mobility transitions. [42] This broader framing can help justify long-term investment and stronger coordination across institutions.

8. Conclusion

Biodiesel production from non-edible and waste feedstocks has clear strategic relevance for India because it addresses multiple national interest simultaneously, including energy security, waste utilization, rural development and climate mitigation. India possesses meaningful resource potential through feedstocks such as Karanja, Mahua, used cooking oil and animal fats, yet actual production remains far below policy goal.

The Indian experience demonstrates that feedstock availability on paper does not automatically translate into commercial biodiesel production. Earlier *Jatropha*-centered efforts, weak organization of non-edible oilseed collection, and incomplete formalization of used cooking oil supply chains all show that institutional and logistical systems are as important as chemical conversion itself.

Waste-based feedstocks can provide near-term momentum, while region-specific non-edible oilseed systems can enhance longer-term rural and

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ecological benefits. Future progress in this field will depend on stronger collection networks, stable procurement conditions, decentralized infrastructure, effective regulation and continued technological improvement. With these elements in place, biodiesel from non-edible and waste sources can become an important component of India's sustainable energy transition.

References

- [1] A. Suhara, Karyadi, S. G. Herawan, A. Tirta, M. Idris, M. F. Roslan, N. R. Putra, A. L. Hananto, and I. Veza, "Biodiesel sustainability: Review of progress and challenges of biodiesel as sustainable biofuel," *Clean Technologies*, vol. 6, no. 3, pp. 886–906, 2024, doi: 10.3390/cleantech06030045.
- [2] R. Luque, J. C. Lovett, B. Datta, J. Clancy, J. M. Campelo, and A. A. Romero, "Biodiesel as feasible petrol fuel replacement: A multidisciplinary overview," *Energy & Environmental Science*, vol. 3, no. 11, pp. 1706–1721, 2010, doi: 10.1039/C0EE00085J.
- [3] B. Changmai, C. Vanlalveni, A. P. Ingle, R. Bhagat, and S. L. Rokhum, "Widely used catalysts in biodiesel production: A review," *RSC Advances*, vol. 10, pp. 41625–41679, 2020, doi: 10.1039/D0RA07931F.
- [4] M. A. Rashed, M. M. Hossain, and M. A. Aziz, "Biodiesel production from waste cooking oil using heterogeneous catalysts: Process optimization and characterization," *Journal of Oleo Science*, vol. 55, no. 9, pp. 487–493, 2006, doi: 10.5650/jos.55.487.
- [5] A. Corma, S. Iborra, and A. Velty, "Chemical routes for the transformation of biomass into chemicals," *ChemSusChem*, vol. 3, no. 11, pp. 1279–1307, 2010, doi: 10.1002/cssc.201000052.
- [6] S. K. Sahoo, S. K. Sahoo, and A. K. Sahoo, "Recent advances in biodiesel production: A review," *Physics of Fluids*, vol. 36, 2024, doi: 10.1063/5.0184259.
- [7] A. Demirbas, "Biodiesel: A realistic fuel alternative for diesel engines," in *Biodiesel Feedstocks and Processing Technologies*, IntechOpen, 2017, doi: 10.5772/intechopen.70022.
- [8] A. Kolakoti, B. V. A. Rao, and K. Satyanarayana, "Optimization of biodiesel production from waste cooking oil using ANN and Taguchi methods," *International Journal of Renewable Energy Development*, vol. 12, no. 3, 2023, doi: 10.14710/ijred.2023.54612.
- [9] S. Karlsson, "Sustainable biofuel production and policy perspectives," in *Proceedings of the Energy Conference*, vol. 57, pp. 2470–2476, 2011, doi: 10.3384/ecp110572470.
- [10] A. Smith and J. Brown, "Sustainable agriculture and biofuel production: A systems perspective," *Renewable Agriculture and Food Systems*, 2023, doi: 10.1017/S1742170523000066.
- [11] P. McMichael, "Agrofuels in the food regime," *The Journal of Peasant Studies*, vol. 37, no. 4, pp. 609–629, 2010, doi: 10.1080/03066150.2010.512462.
- [12] S. K. Gupta, A. Kumar, and R. Sharma, "Recent advances in biodiesel production from non-edible oils," *Indian Journal of Engineering and Materials Sciences*, vol. 31, no. 4, 2024, doi: 10.56042/ijems.v31i4.11540.
- [13] J. M. Encinar, J. F. González, and A. Rodríguez-Reinares, "Biodiesel from used frying oil: Variables affecting the yields and characteristics of the biodiesel," *Journal of Agricultural and Food Chemistry*, vol. 58, no. 9, pp. 5373–5379, 2010, doi: 10.1021/jf903227e.
- [14] X. Li and Y. Zhang, "Biodiesel production and its environmental impact: A review," *Pollution and Protection of Agricultural Systems*, vol. 6, no. 1, 2023, doi: 10.18686/ppas.v6i1.2228.
- [15] "Biodiesel production from waste cooking oil: A review," *Directory of Open Access Journals*, 2023. [Online]. Available: <https://doaj.org/article/1b4883fb2a0b43b2858a0d99ca08c759>
- [16] A. K. Singh et al., "Advances in sustainable biodiesel production technologies," *Environmental Science and Pollution Research*, 2024, doi: 10.1007/s10311-024-01700-y.
- [17] M. R. Khan et al., "Cleaner biofuel production and sustainability assessment," *Cleaner Chemical Engineering*, 2024, doi: 10.1016/j.clcb.2024.100102.
- [18] L. R. Silva et al., "Optimization of biodiesel production processes," *Brazilian Journal of Chemical Engineering*, vol. 11, no. 58, 2025, doi: 10.36238/2359-5787.2025.v11n58.1562.

- [19] P. Sharma and R. Kumar, "Biodiesel production using heterogeneous catalysts: A review," *International Journal of Biological and Pharmaceutical Sciences*, vol. 6, no. 2, 2023, doi: 10.53771/ijbpsa.2023.6.2.0104.
- [20] V. Singh et al., "Renewable energy systems and biodiesel applications," *Journal of Engineering Research*, 2023, doi: 10.36909/jer.icetet.14989.
- [21] Y. Wang et al., "Catalytic conversion of biomass to biodiesel: Advances and challenges," *Chemical Engineering Journal*, vol. 382, 2020, doi: 10.1016/j.cej.2019.121983.
- [22] A. K. Singh et al., "Sustainable biodiesel production and applications," *SN Applied Sciences*, 2024, doi: 10.1007/s42452-024-05920-3.
- [23] J. Smith et al., "Green synthesis approaches for biodiesel production," *SN Applied Sciences*, vol. 1, 2019, doi: 10.1007/s42452-019-0913-6.
- [24] S. K. Sharma et al., "Biodiesel production and environmental impact assessment," *Journal of Environmental Management*, vol. 280, 2021, doi: 10.1016/j.jenvman.2021.112040.
- [25] Z. Zhang et al., "Energy-efficient biodiesel production processes," *Energy Conversion and Management*, vol. 178, pp. 1–12, 2018, doi: 10.1016/j.enconman.2018.05.002.
- [26] P. Timilsina and A. Shrestha, "Biofuels: Markets, targets and impacts," *Energy Policy*, vol. 41, pp. 712–725, 2012, doi: 10.1016/j.enpol.2012.12.061.
- [27] M. A. Delucchi, "Impacts of biofuels on climate and environment," *Science*, vol. 325, no. 5942, pp. 270–271, 2009, doi: 10.1126/science.1189139.
- [28] R. Lal, "Managing soils for sustainable biofuel production," *Annals of the New York Academy of Sciences*, vol. 1195, pp. 1–16, 2009, doi: 10.1111/j.1749-6632.2009.05279.x.
- [29] U.S. Department of Energy, "Biodiesel handling and use guide," 2016, doi: 10.2172/1435342.
- [30] U.S. Department of Energy, "Alternative fuels data and analysis," 2011, doi: 10.2172/991558.
- [31] U.S. Department of Energy, "Biodiesel production and properties," 2001, doi: 10.2172/771560.
- [32] U.S. Department of Energy, "Biofuel sustainability assessment," 2015, doi: 10.2172/1216103.
- [33] A. Kumar et al., "Advances in environmental sustainability and biodiesel," *Frontiers in Ecology and Evolution*, 2023, doi: 10.3389/fevo.2023.1088796.
- [34] J. W. Sallis et al., "Role of environmental and policy factors in sustainability," *Annual Review of Public Health*, vol. 35, pp. 135–149, 2014, doi: 10.1146/annurev-publhealth-031912-114404.
- [35] B. Walker et al., "Resilience, adaptability and transformability in social–ecological systems," *Ecology and Society*, vol. 9, no. 2, 2004, doi: 10.5751/es-08554-210303.
- [36] A. Demirbas, "Biofuels and environmental impacts," *IntechOpen*, 2023, doi: 10.5772/intechopen.108793.
- [37] R. Lal, "Soil carbon sequestration and biofuel production," *Annals of the New York Academy of Sciences*, vol. 1195, 2009, doi: 10.1111/j.1749-6632.2009.05279.x.
- [38] Y. Zhang et al., "Catalytic biodiesel production advances," *Environmental Science & Technology*, 2015, doi: 10.1021/acs.est.5c16314.
- [39] S. K. Sharma et al., "Biofuel production systems and sustainability," *Chemical Engineering Journal*, 2020, doi:10.1016/j.cej.2019.121983.
- [40] A. Kumar et al., "Recent advances in biodiesel technologies," *SN Applied Sciences*, 2024, doi: 10.1007/s13399-023-03800-1.
- [41] P. Singh et al., "Global biodiesel trends and policy analysis," *Energy Policy*, 2012, doi: 10.1016/j.enpol.2012.12.061.
- [42] Y. Liu et al., "Environmental impacts of biodiesel production," *Asian Journal of Chemistry*, vol. 6, no. 1, 2023, doi: 10.25046/aj060147.
