

Performance Evaluation of Biodiesel Production from Edible (Palm and Coconut Oils) and Non-Edible (Jatropha and Neem Oils) Feedstocks: A Comparative Analysis

Sunday Adekanbi Asuku¹, Ibrahim Mohammed Agava², Momohjimoh Abdulmalik Ohida³, Nurudeen Siddiq⁴, Usman Mohammed⁵, Muhammed Adeiza Abdulrazaq⁶

¹Department of Chemical Engineering, Faculty of Engineering, Mewar University India.

²Department of Mechanical Engineering, School of Infrastructure, Process Engineering and Technology, Federal University of Technology Minna, Nigeria.

³Department of Biochemistry (Nutrition) Faculty of life Science, Ahmadu Bello University Zaria, Kaduna State, Nigeria.

⁴Department of Material Science and Engineering, Faculty of Engineering, Kwara State University, Malete, Kwara, Nigeria.

⁵Department of information technology, Faculty of Computing, Bayero University, Kano state Nigeria.

⁶Department of Chemical Engineering, School of Industrial Engineering, College of Engineering, Kaduna Polytechnic, Kaduna Nigeria.

Corresponding author: muhammedabdulrazaq46@gmail.com

Abstract— This study explored the optimization and performance evaluation of biodiesel production using both edible (palm and coconut oil) and non-edible (jatropha and neem oil) feedstocks. Comparative analysis was conducted based on oil content, fatty acid composition, peroxide value, viscosity, free fatty acid (FFA) percentage, specific gravity, and calorific value. The results indicate that edible oils, particularly palm oil, have higher oil content (63-65%) compared to non-edible oils (30-40%), making them more cost-effective for extraction. Fatty acid composition analysis reveals that palm oil, with 51.6% unsaturated fatty acids, is less prone to oxidation compared to jatropha oil (77.5%). Peroxide values show that edible oils are less likely to undergo secondary oxidation, enhancing their storage stability. Additionally, edible oils exhibit lower viscosity (32.15) and FFA (0.91%), which are favorable for efficient combustion and conversion processes. However, non-edible oils offer a higher calorific value, which can produce more power during combustion. Overall, while palm oil emerges as the most viable feedstock for biodiesel production due to its optimal balance of properties, the use of non-edible oil remains limited by extraction costs and susceptibility to oxidation.

Keywords— Biodiesel production, edible oils, non-edible oils, palm oil, coconut oil, jatropha oil, neem oil.

I. INTRODUCTION

The term "biodiesel" refers to a diesel fuel that is derived from vegetable oil or animal fat and is composed of long-chain alkyl esters (methyl, ethyl, or propyl among others). In most cases, biodiesel is produced by the chemical reaction of lipids (such as vegetable oil, soybean oil, animal fat tallow) with fatty acid esters that produce alcohol throughout the production process (Husaini et al., 2025). Recent years have seen an increase in the popularity of biofuels as an alternative fuel due to the fact that they can be replenished and offer other beneficial environmental effects (Lee et al, 2024), it is up to 75% cleaner than fossil fuels when it is burned (Chen et al., 2022). The

number of unburned hydrocarbons, carbon monoxide, and particulate matter in exhaust fumes that are known to cause cancer is significantly reduced as a result of this (Perumal, 2024).

The cetane numbers of biodiesel are determined by the fatty acid profile of the oils or fats that are used in the production of the biodiesel. It was discovered by him that the cetane number was increased in proportion to the length of the carbon chains of the fatty acids and the degree of unsaturation. Because the flash point of biofuels is more than one thousand degrees Fahrenheit higher than that of diesel and was provided as 1600 degrees Celsius, which demonstrated that it may be categorised as a non-flammable liquid, biofuels have been labelled as safe fuels. Furthermore, the toxicity of biofuels is at least fifteen times lower than that of diesel, the flash point of petrol is 45 degrees Celsius, whereas the flash point of petroleum diesel is 64 degrees Celsius. (Dahiya, 2020; Hedden, 2020).

Biodiesel is a renewable liquid biofuel that can be utilized in diesel engines either in its pure form or as a blend with conventional diesel (Jamrozik et al., 2024). It is produced through chemical processes, typically involving the transesterification of vegetable oils or animal fats with an alcohol (Bojesomo et al., 2023). Blended fuels are designated using the notation "Bx," where x indicates the percentage of biodiesel in the mixture. For example, B5 contains 5% biodiesel and 95% petroleum diesel, while B100 refers to pure biodiesel (Ruatpuia et al., 2024).

Similarly, Hoti et al. (2024) emphasized the importance of phytochemical profiling in evaluating the bioactive components of plant materials. Their findings revealed that the chemical composition, particularly the presence of flavonoids and tannins, strongly influences functional performance. This underscores the critical role of fatty acid composition in biodiesel feedstocks, where the chemical structure determines

properties such as viscosity, oxidative stability, and overall fuel performance (Hoti et al., 2024).

1.1 Optimization in Biodiesel Production

Optimization in biodiesel production refers to the systematic adjustment of process variables to achieve maximum yield, improved quality, and cost-effectiveness. Since biodiesel properties are strongly influenced by feedstock type, alcohol-to-oil molar ratio, catalyst concentration, reaction temperature, and reaction time, identifying the best combination of these parameters is critical. For instance, edible oils such as palm and coconut generally provide higher yields due to their favorable fatty acid composition, while non-edible oils like jatropha and neem require careful process optimization to overcome issues such as high free fatty acid content and impurities (Haq et al., 2023). Techniques such as Response Surface Methodology (RSM), Taguchi design, and genetic algorithms have been widely applied to model and optimize biodiesel processes (Al-Habaibeh et al., 2000; Mishra et al., 2025). These approaches allow researchers to evaluate interactions between multiple variables, reduce experimental runs, and identify optimal conditions for transesterification. Through optimization, improvements can be achieved not only in biodiesel yield but also in fuel properties such as viscosity, flash point, oxidative stability, and cold flow performance (Hybrid et al., 2023). Therefore, optimization ensures that biodiesel derived from both edible and non-edible feedstocks meets ASTM and EN standards while also improving the sustainability and economic feasibility of biodiesel production on a commercial scale (Iweka et al., 2023).

Recent studies provide useful insights into the role of feedstock optimization, phytochemical evaluation, and process characterization, which are highly relevant to biodiesel production research. Abdulrazaq et al. (2025) demonstrated that blending different agricultural raw materials such as sorghum, Bambara nut, pumpkin seed, and banana flour significantly enhanced nutritional and sensory properties of cereals. This highlights the importance of optimizing feedstock combinations to achieve improved quality outcomes, a concept directly applicable to blending edible (palm and coconut) and non-edible (jatropha and neem) oils for biodiesel production (Abdulrazaq et al., 2025).

Furthermore, Lams et al. (2024) explored the extraction and characterization of natural dyes from *Eucalyptus globulus*, focusing on optimizing the extraction solvents and process conditions. This had a major impact on yield and performance features. This reflects the same principle in biodiesel production, where optimizing reaction conditions such as catalyst concentration, temperature, and reaction time directly affects biodiesel yield and quality. Collectively, these studies demonstrate that feedstock selection, compositional analysis, and process optimization are key drivers for enhancing biodiesel production efficiency and performance (Lams et al., 2024).

1.2 Biodiesel Feedstock

Refined vegetable oils, in particular soybean oil and canola oil, have been the most prevalent sources of feedstock for biodiesel production, between the years 2014 and 2017, about

fifty percent of the feedstock inputs for biodiesel were comprised of soybean oil. Growing soybeans is mostly done in the Midwest, which is also where the majority of the capacity for producing biodiesel is situated, as still around 2014 to 2017, there was a about thirty percent rise in the utilisation of soybean oil for the manufacture of biodiesel (Bashir et al., 2022).

Other sources of feedstock for biodiesel include rendered animal fats and recycled cooking oils, both of which have very little or no value for human consumption. The production of biofuel from yellow grease, which is used cooking oil from restaurants, has grown by about forty percent over the previous four years, going from around one billion to one and a half billion pounds. Over ten percent of the entire biofuel raw material came from yellow grease in 2017. White grease, which is pork fat, and tallow, which is beef fat, each contributed around three to six percent of the total feedstock inputs during the years 2014 and 2017 (Ravindra et al., 2023; Ruatpuia et al., 2024).

1.2.1 Palm Oil (*Elaeis Guineensis*) as Feedstock for Biodiesel

The oil palm (*Elaeis guineensis*), believed to have originated in the tropical rainforests of West Africa, particularly within a primary belt stretching from Angola and the Congo through Cameroon, Côte d'Ivoire, Ghana, Liberia, Nigeria, Sierra Leone, and Togo, has been cultivated and utilized for thousands of years, with every part of the tree holding economic or domestic value, and while the traditional processing of its fruits to extract deeply colored and richly flavored edible oil has long been central to West African cuisine despite being labor-intensive and inefficient, modern large-scale cultivation is now concentrated in regions such as Nigeria's South East Zone and the Niger Delta, where the mature palms, characterized by single stems reaching up to 20 meters and pinnate leaves extending 3–5 meters, continue to serve as a vital agricultural and industrial resource (Oil et al., 2024; Phase et al., 2023). Beyond its agricultural importance, palm oil serves as a crucial food item with nearly 90% of global production directed toward food products and less than 10% utilized in industrial manufacturing, and owing to its diverse applications its demand continues to rise alongside population growth and improvements in living standards; compared to other major vegetable oils such as rapeseed and soybean, palm oil is more environmentally efficient, producing significantly higher yields per hectare with reduced land use and lower energy inputs, while also being valued for its medicinal and nutritional properties including the management of malaria, high blood pressure, high cholesterol, and cyanide poisoning, prevention of vitamin A deficiency, and potential benefits for cancer patients, brain-related disorders, aging populations, weight loss, and metabolic health, and in addition to its culinary use for frying and cooking, palm oil is widely applied in the manufacture of cosmetics, soaps, toothpaste, waxes, lubricants, and inks, as well as occasionally serving as a feedstock in biodiesel production in the form of Palm Oil Methyl Ester (Maria Chinecherem et al., 2023; Sharma et al., 2022)

1.2.2 Coconut (*Cocos Nucifera*) as a Potential Feedstock for Biodiesel

Cocos nucifera L., sometimes known as the coconut, is a tree that is regularly farmed for its several applications, mostly

due to the nutritional and medical benefits it offers. Consider, for instance, raw kernel, tender coconut water, copra, coconut oil, coconut cake, coconut toddy, coconut shell and wood-based products, coconut leaves, coir pith, and more. Coconut may be used to create a variety of items, and all of them are examples of this (Santana et al., 2024). All of its components are utilised in some fashion or another in the day-to-day activities of the people who live in the places where coconuts are traditionally grown. It is the only source of a wide variety of natural materials that may be used in the production of industrial goods as well as medications that are used to treat a wide range of disorders (Adou et al., 2025).

1.2.3 Neem (Azadirachta Indica) as a Potential Feedstock for Biodiesel

Neem, also known as *Azadirachta indica*, is a member of the family Meliaceae and is considered to be one of the most valuable and ideal tree species that can be found in India, due to the fact that it can thrive in a broad variety of soils, up to a pH of 10, it is considered to be one of the most significant and versatile trees on the Indian subcontinent (Kumar et al., 2018; Musawa et al., 2024). Because it may be utilised in a wide variety of contexts, Indian farmers have been cultivating it since the Vedic time, and it has since become an integral element of Indian culture, in India, it may be found all across the nation and can thrive in all agroclimatic zones, with the exception of high and cold locations as well as dam sites (Neto et al., 2023). This method is utilised by farmers solely for the purpose of satisfying the local need for timber, fodder, fuelwood, and different therapeutic characteristics. It does not compete with annual crops for the limited amount of soil moisture that is available because of its deep tap root structure (Musawa et al., 2024).

Neem oil can be golden yellow, yellowish brown, reddish brown, dark brown, greenish brown, or brilliant red in colour. The colour of the oil is mostly determined by the number of days that the neem is soaked in water. It has a smell that is described as being a combination of the smells of peanuts and garlic, and it is rather potent. Triglycerides make up the majority of its composition, and it also contains a great deal of triterpenoid chemicals, which are the ones responsible for the bitter flavour. It is hydrophobic by its very nature; thus, it is prepared with surfactants in order to emulsify it in water for the purposes of application application (Mahmoud et al., 2024).

Azadirachtin is the triterpenoid found in neem oil that has received the greatest attention and research. Researchers believe that nimbin, a distinct form of triterpenoid, is responsible for neem oil's antibacterial, antifungal, antipyretic, and antihistamine effects. There are also a number of sterols found in neem oil, including as campesterol, beta-sitosterol, and stigmasterol (Mini et al., 2022).

1.2.4 Jatropha (Jatropha Curcas) as Feedstock for Biodiesel Production

Jatropha Oil

Jatropha oil is the name given to the oil that is extracted from the seeds of the jatropha plant, which is a plant that may be found growing in all common and marginal areas, one of the plant species that is utilised for the purpose of oil extraction is referred to as *Jatropha Curcas*, due to the high level of toxicity

that *jatropha curcas* possesses, it is not ingested by humans or any other living organisms (Jaspal et al., 2023).

The extraction of oil from the seeds of jatropha, which may be utilised as an alternative source of energy, is the primary objective of expanding jatropha cultivation around the globe (Haq et al., 2023). In the same way that jatropha farming has become increasingly important, jatropha oil extraction techniques have also gained weight, as a result of the fact that the oil that is produced from jatropha seeds is the principal source of biofuel, the process of extraction techniques has also become crucial (Ruatpuia et al., 2024).

Jatropha oil, which is toxic and unsuitable for human consumption, is extracted from seeds and processed into high-quality biofuel for use in diesel engines, while the residual byproducts are further utilized as biomass fuel for energy generation and as natural fertilizer, and although its production typically requires two distinct processing steps to achieve yields of up to 92%, failure to optimize these processes can reduce yields to below 85% (Bamgboye et al., 2021).

1.3 Classifications of Biodiesel Feedstock

1.3.1 Classification as Edible and Non-Edible Oil.

Edible oils, as the name implies, are those suitable for human consumption and widely used in food applications (Gonz et al., 2023). They are valued for their high nutritional content and generally require minimal processing to meet safety and sanitary standards (Perumal, 2024), while their primary demand lies in the food sector, a significant portion of vegetable oils also falls under this category, making them readily available as potential feedstocks for biodiesel production (Zheng et al., 2025). The triglycerides that are derived from plants are known as vegetable oils. Since the beginning of human history, some oils have been a part of human civilisation (Ruatpuia et al., 2024). There are a variety of oils, both edible and non-edible, that are used as fuel, such as with oil lamps and as an alternative to fuels derived from petroleum (Haq et al., 2023).

Non-edible oils refer to vegetable oils and petroleum-based oils that are unsuitable for human consumption but hold significant value in the industrial sector. This category also includes certain animal-derived lipids that are not consumed as food (Ruatpuia et al., 2024; Tiwari et al., 2024). These oils differ from edible oils in several ways, including their composition, processing requirements, and applications (Tiwari et al., 2024).

Non-edible vegetable oils, though unsuitable for human consumption due to harmful components, offer a cost-effective and sustainable alternative for biodiesel production, providing advantages such as liquid nature, portability, renewability, improved combustion efficiency, lower sulphur and aromatic content, and higher biodegradability compared to food-grade vegetable oils (Adekunle et al., 2024).

1.3.2 Classification Based on Generation

First-generation biodiesel, also referred to as conventional biodiesel, is produced from food crops such as soybean, palm, coconut, rapeseed, and sunflower that are cultivated on arable land, with their sugars, starches, or vegetable oils converted into biodiesel or ethanol through processes such as

transesterification or yeast fermentation; while this approach established the foundation for large-scale biodiesel production, it has raised concerns due to direct competition with food supply, rising food prices, and the unsustainable use of agricultural land and resources (Ishola et al., 2024).

Second-generation biodiesel encompasses fuels derived from a wide variety of non-food biomass resources, including lignocellulosic materials, woody crops, agricultural residues, waste plant matter, non-edible oils such as jatropha, and municipal solid waste; unlike first-generation biodiesel, which depends on sugars, starches, and vegetable oils extracted from food crops cultivated on arable land, second-generation feedstocks are typically sourced either as byproducts of primary harvests, from lands unsuitable for food production, or from waste streams that require little to no additional inputs such as fertilizer or irrigation, thereby minimizing competition with food resources, reducing environmental burdens, and providing a more sustainable pathway within the global carbon cycle for biodiesel production (Ahmad et al., 2023).

Third-generation biodiesel is derived primarily from algae, which can contain more than 50% oil and be cultivated in ponds or bioreactors without competing for cropland or freshwater, offering significant sustainability advantages over crop-based feedstocks, as demonstrated by research programs such as the U.S. National Renewable Energy Laboratory's Aquatic Species Program (1978–1996) and subsequent feasibility studies showing that algal oils can be efficiently extracted and converted into biodiesel, with residual biomass further processed into ethanol, making algaculture a promising though still developing pathway toward large-scale, cost-effective biodiesel production (Sadaqat et al., 2024).

Fourth-generation biodiesel is produced on non-arable land and, unlike third-generation biodiesel, does not require biomass degradation, but instead relies on advanced technologies such as electrofuels and photobiological solar fuels that utilize engineered microorganisms or direct solar energy capture, with some variants achieving near-zero or even carbon-negative footprints, thereby representing a highly sustainable and futuristic approach to biofuel production that addresses both land-use concerns and greenhouse gas emissions (Ashokkumar et al., 2024).

II. MATERIALS AND METHODS

2.1 Materials

2.1.1 Raw Materials:

Dried *Jatropha curcas* seeds, dried Neem (*Azadirachta indica*) seeds, mature coconut (*Cocos nucifera*) endosperm (kernel), fresh palm (*Elaeis guineensis*) fruit mesocarp.

2.1.2 Chemicals and Reagents:

Distilled water, denatured ethanol (95%), neutralized solvent (for titration, e.g., isopropanol/toluene mix or ethanol), sodium Hydroxide (NaOH) pellets, potassium Hydroxide (KOH) pellets, phenolphthalein indicator solution (1% in ethanol), dleic acid (standard for calibration).

2.1.3 Equipment and Glassware for Extraction:

Mechanical hydraulic press or oil expeller, nutcracker or decorticator, grater (for coconut), digester (for palm fruit), hilter

press or muslin cloth, funnels, amber-colored glass bottles for storage

2.1.4 For Analysis:

Analytical weighing balance (± 0.0001 g precision), rotary digital viscometer (e.g., Brookfield-type) with appropriate spindles (e.g., Spindle No. 2), pycnometers (25 mL or 50 mL) or specific gravity bottles, circulating water bath (for temperature control at 20°C, 40°C), conical flasks (250 mL), burettes (50 mL), pipettes and measuring cylinders, volumetric flasks, hot plate, vortex mixer (optional for mixing).

2.2 Methodology

2.2.1 Oil Extraction Methodology

The method of extraction was selected based on the nature of the feedstock to maximize oil yield while preserving its native chemical properties.

- i. *Jatropha curcas* and Neem Seeds: The seeds were first decorticated to remove the shells. The obtained kernels were then mechanically crushed using a motorized hydraulic press. The expelled crude oil was collected and filtered to remove suspended solid particles and mucilaginous matter, resulting in the oil used for analysis.
- ii. Coconut: Fresh coconut kernel (endosperm) was grated, dried, and the oil was extracted using a mechanical expeller press. The crude coconut oil was filtered to obtain a clear sample.
- iii. Palm Oil: Extraction was performed on the palm fruit mesocarp. The fruits were sterilized, stripped, and digested to separate the pulp. The oil was then mechanically pressed out from the digested mash and clarified through settling and filtration.

All extracted crude oils were stored in airtight, amber-colored glass containers under cool, dark conditions to prevent photodegradation and oxidation prior to analysis.

2.2.2 Analysis of the Different Oil Feedstock

The crude *Jatropha curcas* seed oil, Neem seed oil, coconut oil and palm oil were analyzed in terms of their physicochemical properties in accordance with the American Society for Testing and Material (ASTM) standard (ASTM D6751).

2.2.2.1 Determination of Oil Content in Feedstock

The oil content of the feedstocks was determined using the Soxhlet solvent extraction method with n-hexane as the extracting solvent, in which the seeds were first decorticated (where necessary), ground into a fine powder using a mechanical grinder, and approximately 10 g of the powdered sample was accurately weighed and oven-dried at 105 °C for 2 hours to remove moisture before being placed in a pre-weighed cellulose extraction thimble, which was inserted into the Soxhlet apparatus connected to a pre-weighed round-bottom flask containing 150–200 mL of n-hexane and fitted with a condenser; the solvent was then heated to reflux and allowed to cycle continuously for 6–8 hours to ensure exhaustive extraction of lipids, after which the solvent–oil mixture collected in the flask was subjected to solvent removal using a rotary evaporator, and the resulting oil residue was further dried in an oven at 105 °C for 1 hour to eliminate traces of residual

solvent, cooled in a desiccator, and weighed with high precision, with the oil yield finally calculated as a percentage of the initial dry sample weight, thereby providing a quantitative measure of the total lipid content in the feedstock.

2.2.2.1 Determination of Fatty Acid Composition (Gas Chromatography)

The fatty acid composition of the oils was determined by first converting the triglycerides into more volatile fatty acid methyl esters (FAMES) through esterification, in which approximately 100 mg of oil was dissolved in 4 mL of n-hexane, treated with 0.2 mL of 2M methanolic KOH, vortexed, allowed to settle, and the upper hexane layer containing the FAMES was collected and injected (1 µL) into a gas chromatograph equipped with a flame ionization detector (GC-FID) and a polar capillary column (e.g., DB-WAX or HP-INNOWax), using helium or nitrogen as the carrier gas under an oven program of 150–240 °C at 4 °C/min, with injector and detector temperatures set at 250 °C and 260 °C respectively, after which the fatty acids were identified by comparing the retention times of sample peaks with those of a known FAME standard mix and quantified based on peak area normalization to express each fatty acid as a percentage of the total composition.

2.2.2.3 Determination of Peroxide Value

The peroxide value (PV) of the oils was determined by weighing 5 g of sample into a 250 mL iodine flask, dissolving it in 30 mL of a 3:2 (v/v) glacial acetic acid/chloroform mixture, adding 0.5 mL of saturated KI solution, allowing the mixture to stand in the dark for 5 minutes, then adding 30 mL of distilled water and titrating immediately with 0.01 M sodium thiosulfate solution until the yellow colour nearly disappeared, followed by the addition of 0.5 mL starch indicator (blue colour) and continuing the titration to a colourless endpoint, with a blank determination run in parallel, and the PV expressed as milliequivalents of active oxygen per kilogram of oil using the formula $PV = [(S - B) \times M \times 1000] / W$, where S is the titrant volume for the sample (mL), B is the blank (mL), M is the molarity of $Na_2S_2O_3$, and W is the weight of the sample (g).

Peroxide Value (meq O_2 /kg oil) = $[(S - B) \times M \times 1000] / W$
Where:

- S = Volume of $Na_2S_2O_3$ used for sample (mL)
- B = Volume of $Na_2S_2O_3$ used for blank (mL)
- M = Molarity of $Na_2S_2O_3$ solution
- W = Weight of sample (g)

2.2.2.4 Viscosity Determination

The viscosity was determined by using spindle No.2 of rotary digital viscometer, Viscosity refers to the thickness of the oil, and is determined by measuring the amount of time taken for a given measure of oil to pass through an orifice of a specified size. Viscosity measurement were taken for the three fuel samples (Tucker et al., 2023).

2.2.2.5 Determination of Free Fatty Acid and Acid Value

The acid value of the oils, which represents the amount of free fatty acids present and hence the degree of hydrolytic rancidity, was determined by accurately weighing 10 g of oil into a 250 mL conical flask, dissolving it in 50 mL of hot neutralized ethanol containing phenolphthalein as an indicator, and titrating the hot solution with standardized 0.1 M NaOH

while shaking constantly until a faint but permanent pale pink colour persisted for at least 30 seconds, after which the percentage free fatty acid (expressed as oleic acid) was calculated using % FFA = $[(V \times M \times 282) / (W \times 10)]$ and the acid value was expressed as mg KOH per gram of oil using AV = $[(V \times M \times 56.1) / W]$, where V is the volume of NaOH used (mL), M is the molarity of the NaOH solution, W is the weight of the sample (g), 282 is the molecular weight of oleic acid, and 56.1 is the molecular weight of KOH.

$$\% \text{ FFA (as Oleic Acid)} = [(V \times M \times 282) / (W \times 10)]$$

$$\text{Acid Value (mg KOH/g)} = [(V \times M \times 56.1) / W]$$

Where:

V = Volume of NaOH used (mL)

M = Molarity of NaOH solution

W = Weight of sample (g)

282 = Molecular weight of oleic acid

56.1 = Molecular weight of KOH

2.2.2.6 Determination of Density/Specific Gravity

This was achieved by used of weighing balance, density bottles and circulating bath. The density bottles were washed, dried and marked, some amounts of the test samples were put into the density bottle and after which the weight is taken (Mcguire et al., 2025).

Weight of empty density bottle = A

Weight of bottle + water = B

Weight of bottle + oil = C

The respective densities were then calculated from the results gotten.

Density = mass/weight of oil/ volume of oil

Specific gravity = weight of xml of oil/ weight of xml of water = C-A/B-A

The density (specific gravity) of the oils was determined using a specific gravity bottle (pycnometer). Specific gravity is defined as the ratio of the weight in air of a given volume of oil at a specified temperature to the weight of an equal volume of water at the same temperature. For the measurement, a clean, dry pycnometer was first weighed empty, then filled with distilled water maintained at 20 °C and reweighed.

$$\text{Specific gravity} = \frac{\text{weight of oil}}{\text{weight of water at } 20^\circ\text{C}}$$

The bottle was subsequently emptied, dried, filled with the oil sample, and weighed again, after which the specific gravity value was calculated (Akinoso et al., 2023).

2.2.2.7 Determination of Calorific Value

The calorific value of the oils was determined using a bomb calorimeter (e.g., Parr 6100) calibrated with benzoic acid, where approximately 0.8–1.0 g of accurately weighed oil was placed in a combustion capsule fitted with a fuse wire, sealed in the bomb, charged with pure oxygen (25–30 atm), and submerged in a calorimeter bucket containing a known mass of water, after which the sample was electrically ignited, the resulting temperature rise of the water was precisely measured, and the gross calorific value (GCV) in MJ/kg was automatically calculated by the instrument software with corrections for fuse wire and acid formation, while the net calorific value (NCV) was obtained by applying an additional correction for the latent heat of vaporization of water formed during combustion (Borowik et al., 2024).

III. RESULTS AND DISCUSSION

Results

3.1 Oil Content in Feedstock

Figure 1.1 shows Oil content of the different oil feedstock. It was observed from the table that the oil content of the feed varies in the yield percentage from 30 %, 40%, 60% and 65% for neem seed oil, jatropha curcas, coconut oil and palm oil respectively. The higher oil concentration of the edible oils (palm oil and coconut oil) compared to the non-edible oils (jatropha and neem seed oil) is demonstrated by this. This is a very important factor to consider when selecting the feedstock to use for biodiesel production as the oils with low oil (as in the case of the non-edible oils) content will be expensive to extract the quantity that may be required for large scale biodiesel production as well as consuming time and man power which may not be cost effective. In the same way, the oils with high oil content (as in the case of the edible oils) will be cost

effective in terms extraction, raw seed quantity, time of extraction and man power required. With respect to oil content, it can be said that edible oils (especially palm oil with oil content of 63-65%) is more viable for biodiesel production than the non-edible oils (especially neem oil with oil content of 20-30%). Though the edible oils appear to be more viable for biodiesel production, but may face competition in terms of raw material from consumers as it is edible. Oils for example is the most consumed edible oil in the world (Ruatpuia et al., 2024) and appear to be the most viable in terms of oil content, for biodiesel production as shown in Figure 1.1.

3.2 Fatty Acid Composition

Figure 1.2, also shows Fatty acid composition of the different oil feedstock in terms of the saturated and unsaturated fatty acid percentage. This property of the oil is very important when selecting feedstock for biodiesel production. This is because, the free fatty acid composition, help to know the extent the feedstock can be oxidized.

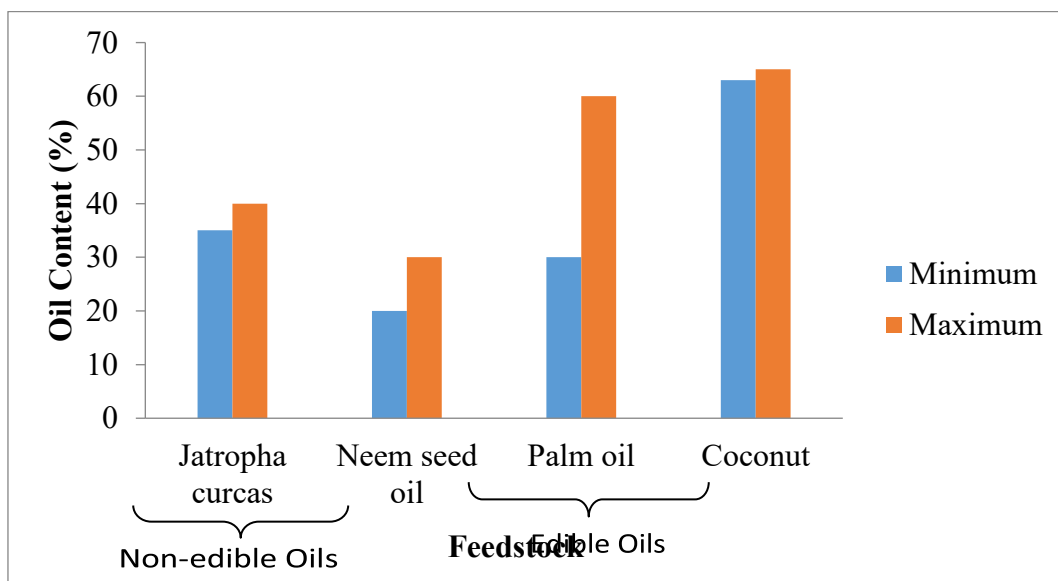


Figure 1.1: The Oil content of the different Feedstock

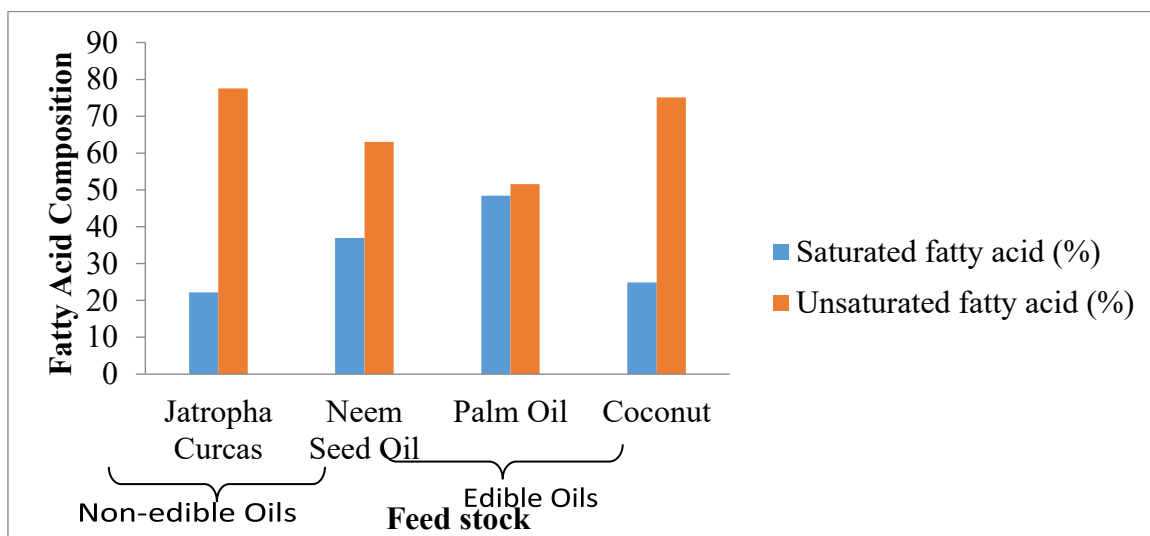


Figure 1.2: Fatty Acid Composition of the Different Oil Feedstock

Jatropha contain 22.5% saturated fatty acid and 77.5% unsaturated fatty acid, Neem seed oil contain 37.0% saturated fatty acid and 63.0% unsaturated fatty acid, Coconut oil contains 24.9 % saturated fatty acid and 75.1% unsaturated fatty acid and palm oil contains 48.4% saturated fatty acid and 51.6% unsaturated fatty acid. On the average, the non-edible contains 29.5% saturated fatty acid and 70.5% unsaturated fatty acid while, the edible oils contains 36.65% saturated fatty acid and 73.35% unsaturated fatty acid. Oils with high unsaturated fatty acid, if used to produce biodiesel tends to oxidize on storage thereby changing the physico-chemical properties of the biodiesel (Jeon et al., 2016; Koppireddi et al.,2016; Song et al.,2013), which limits the viability of the oil. With regards to fatty acid composition, it can be said that the non-edible oils are not viable for biodiesel production as they have high tendency to oxidize on storage thereby causing change the physico-chemical properties of the diesel which may affect the efficiency. In simple sense, oils with high unsaturated fatty acid, if used to produce biodiesel, the resulting biodiesel will not be durable and therefore less viable in comparison with edible Oil. Among the edible oils, palm oils has less unsaturated fatty acid (i.e. 51.6%) and therefore more viable than coconut oil which is of higher unsaturated fatty acid (i.e. 75%). With respect to the non-edible oils, biodiesel form neem seed oil is less likely to iodized when kept in storage as it is of less unsaturated fatty acid (i.e. 63%) when compared to jatropha oil which is of higher unsaturated (i.e. 77.5%) and therefore less viable. Palm oil happens to be the most viable oil for biodiesel production when considering its fatty acid composition but is less likely to be used, being the most consume edible oil.

3.3 Peroxide Value

Figure 1.3, shows some physico-chemical properties of the different feedstock obtained from their characterization. Their peroxide values were 1.93, 1.49, 5.9 and 16 for Jatropha curcas, neem seed oil, palm oil and coconut oil respectively. The edible oils (ie palm oil and coconut oil) have average peroxide value of 10.95 while the non-edible oils (i.e. neem seed oil and jatropha curcas) have average peroxide value of 1.695. The degree of primary oxidation of oils (rancidification) is measured by the peroxide value (PV), which is influenced by

temperature, time, and light. Rancidity of oils can produce potentially toxic compounds as a result of break down in the chemical structures of the oil, leading to the production of unwanted odours and flavours. The result shows that the non-edible oils are more likely to undergo secondary oxidation thereby producing unwanted odours and flavours, which is toxic and not environmentally friendly with respect to the peroxide value the edible oils are less likely to undergo secondary oxidation and are therefore more viable than the non-edible oils. Coconut oil seems to be more viable in terms of its peroxide value (16) but most expensive of the feedstock.

3.4 Viscosity

Figure 1.4 also show the viscosity of the different feedstock measured at 40°C. Their viscosities were 42.8, 49.7, 35.41, and 27.2 16 for Jatropha curcas, neem seed oil, palm oil and coconut oil respectively. The average viscosity for the edible oils is 32.15, while that of the non-edible oils is 46.25. The viscosity of the non-edible oils was found to be greater than that of the edible oils. Biodiesel from oils with low viscosity tends to combust effectively in the diesel engine than those of high viscosity. Thus, biodiesel from edible have more potential for fuel application than those from non-edible oils.

3.5 Free Fatty Acid Composition

The figure 1.5 free fatty acid (FFA) composition of the oils is perhaps the most important property of the feedstock in the production of biodiesel in terms of conversion. The free fatty acid obtained from the analysis were; 14.0, 1.2, 0.77 and 1.05 for Jatropha Curcas, neem seed oil, palm oil and coconut oil respectively. The edible oils have an average FFA of 0.91% (low), while that of the non-edible oils is 9.1% (high). The free fatty acid of oil feedstock that must be used for biodiesel production must not be greater than 1%. Otherwise it will lead to high catalyst consumption and low yield in the biodiesel produce. In other to bring lower the FFA of oils of higher FFA >1%, the oils are first made to undergo esterification so as to lower the FFA before the transesterification process that will produce the biodiesel. The FFA value shows that the edible oil is more viable for the production of the biodiesel, especially the palm oil with FFA value 0.77% and would not require any esterification before the transesterification.

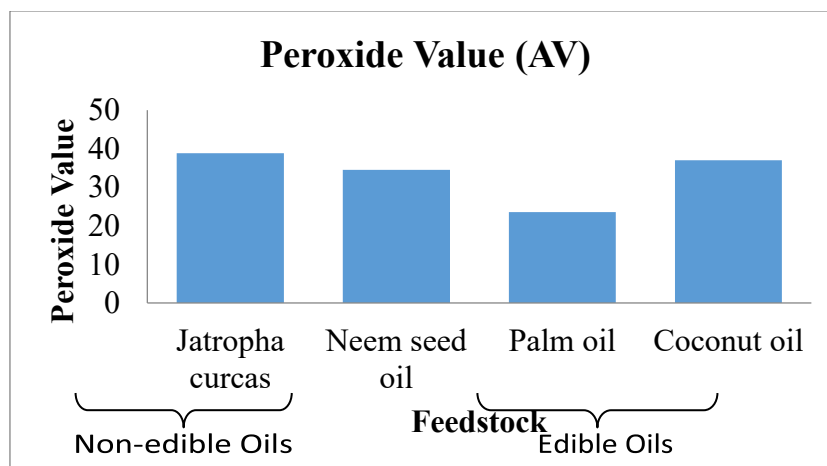


Figure 1.3: Peroxide Value of the Different Feedstock

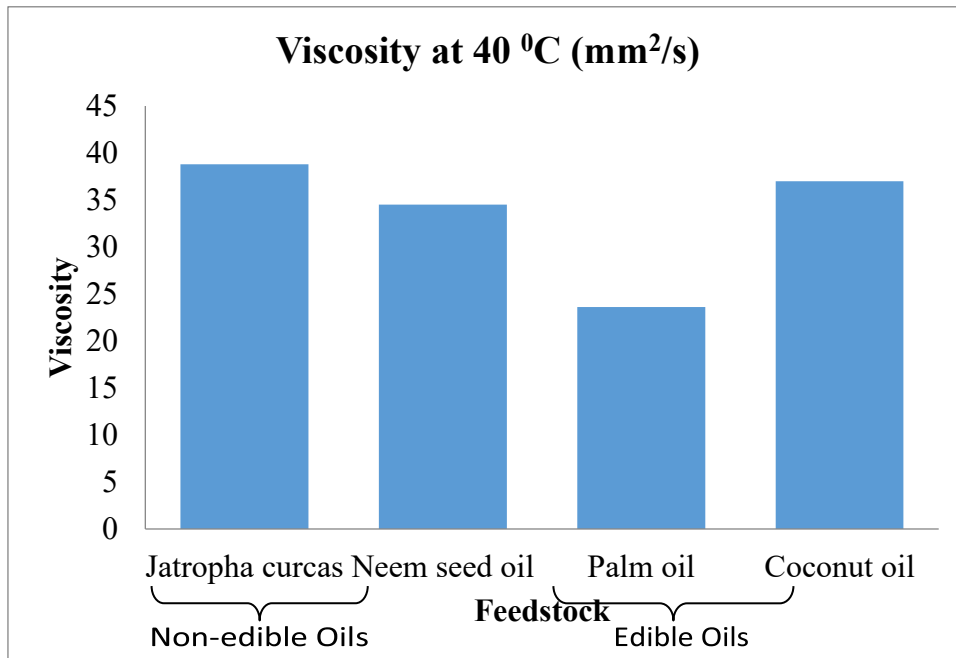


Figure 1.4: Viscosity of the Different Feedstock

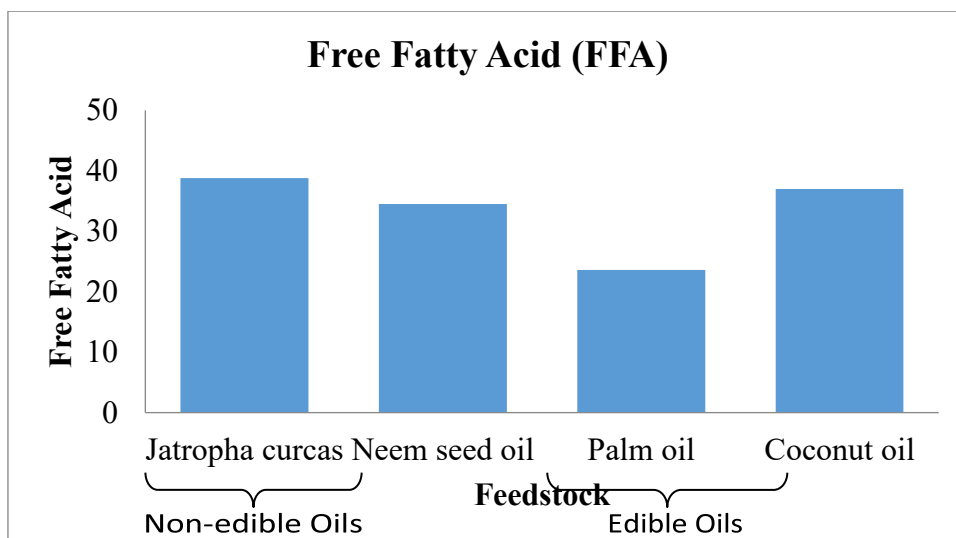


Figure 1.5: Free Fatty Acid Percentage of the Different Feedstock

3.6 Specific Gravity

The figure 1.6 specific gravity obtained from the analysis were, 872kg/m³, 912 kg/m³, 869 kg/m³ and 925 kg/m³ for Jatropha Cucas, neem seed oil, palm oil and coconut oil respectively. Palm oil has the lowest specific gravity and therefore more viable as the specific gravity of biodiesel is usually higher than that of petro-diesel. Coconut oil happens to have the highest specific gravity and therefore the least viable. The result of shows that specific gravity is not a function of whether the feedstock is edible or non-edible oil but rather it is peculiar with each of the feedstock. Biodiesel is often blended with petro-diesel because of its high specific gravity as those with high specific gravity easily cause knocking to engines than those with low specific gravity. Feedstock with low specific

gravity is mostly preferred to those of higher specific gravity and therefore more viable.

3.7 Calorific Value

The figure of 1.7 shows the calorific value of the feedstock obtained from the analysis as follows, 38.8MJ/kg, 34.5MJ/kg, 23.6MJ/kg and 37MJ/kg. Non-edible oils edge over edible oils in terms of calorific value. The calorific value of any oil is the amount of heat released by a unit weight or unit volume of a substance during complete combustion. The term calorific value of the fuels is very important as selection of oil for the production of biodiesel for the diesel engines. If the oil has higher calorific value it will result in the production of biodiesel with high calorific value which will have tendency to produce more power in the engine. In the same way, if the oil has low calorific value it will result in the production of biodiesel with

less calorific value which will tend to burn inefficiently thus causing lot of exhaust and air-pollution.

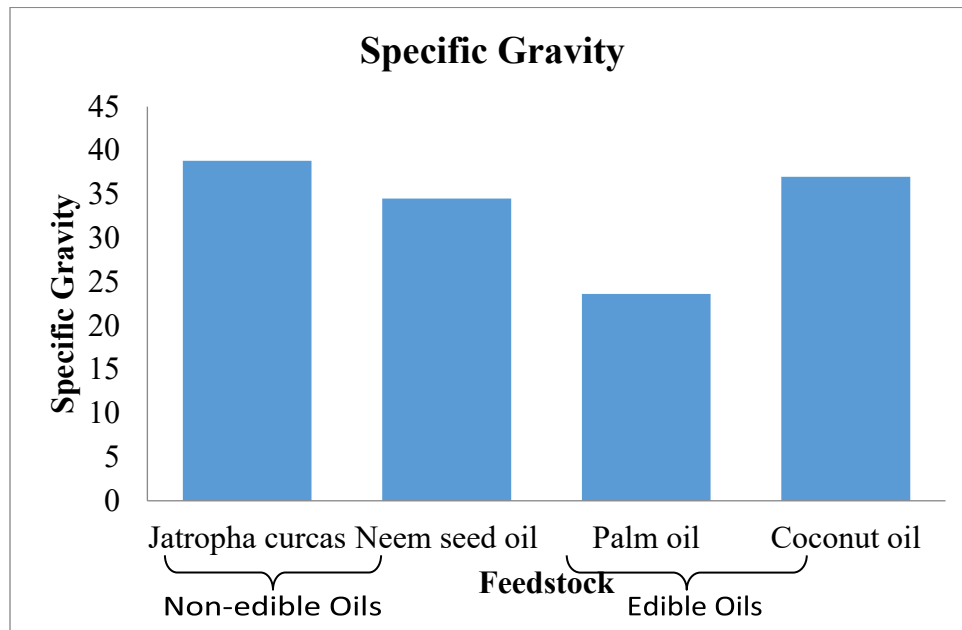


Figure 1.6: Specific Gravity of the different Feedstock

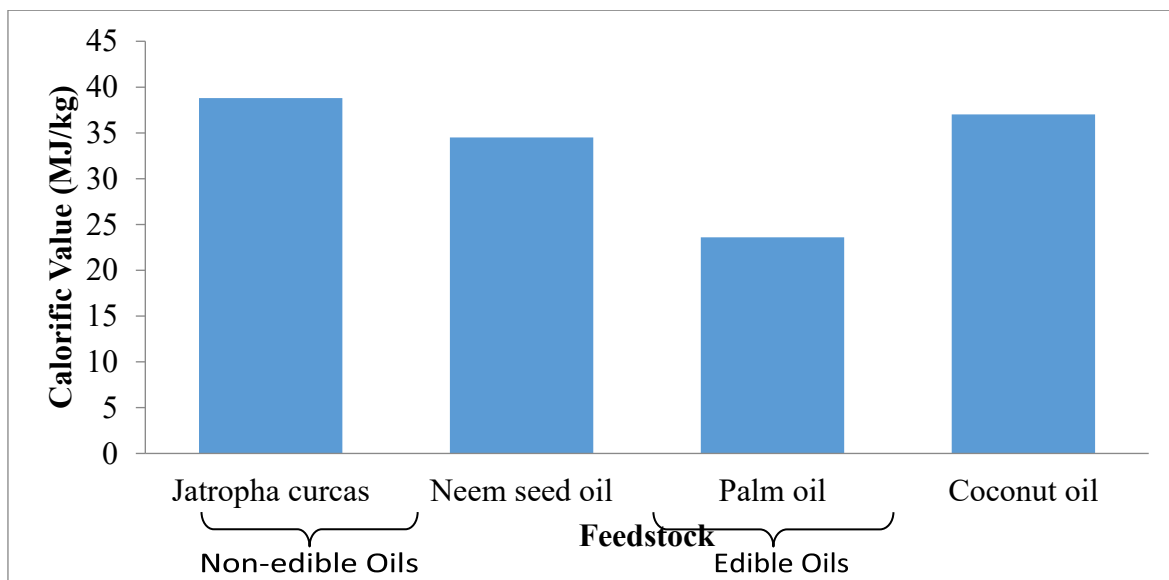


Figure 1.7: Calorific Value of the Different Feedstock

IV. CONCLUSION

In this comparative study, the viability of edible and non-edible oils for biodiesel production was evaluated based on key physico-chemical parameters. The results indicate that edible oils, particularly palm oil, are more suitable for biodiesel production due to their high oil content, low FFA percentage, lower viscosity, and better oxidative stability. Palm oil, with a high oil yield (63-65%), low FFA (0.77%), and moderate unsaturated fatty acid content (51.6%), does not require esterification prior to transesterification, reducing processing

costs and time. In contrast, non-edible oils like jatropha and neem face challenges due to lower oil yields, higher FFAs, and a greater tendency to oxidize, impacting the quality and durability of the biodiesel produced. Despite non-edible oils offering higher calorific values, their overall viability is hindered by extraction inefficiencies and processing complexity. Therefore, while edible oils are optimal for biodiesel production, considerations around food security and competition for edible oil resources may necessitate further research into improving the efficiency and stability of non-edible oil-based biodiesel production.

REFERENCE

[1]. Abdulrazaq, M. A., Kaduna, F. P., Muhammad, U. G., & Alsharksi, A. (2025). Development and Quality Assessment of Cereals Made from Malted Sorghum , Bambara Nut , Pumpkin Seed , and Mature Unripe Banana Flour Blend. *African Journal of Biological Sciences*, 7(2), 71–98. <https://doi.org/10.48047/AFJBS.7.2.2025.73-98>

[2]. Adou, A. I., Brelle, L., Marote, P., Sylvestre, M., & Cebrián-torrejón, G. (2025). *Physicochemical Properties of Coconut and Waste Cooking Oils for Biofuel Production and Lubrication*. 1–13.

[3]. Ahmad, S., Jafry, A. T., Haq, M. ul, Abbas, N., Ajab, H., Hussain, A., & Sajjad, U. (2023). Performance and Emission Characteristics of Second-Generation Biodiesel with Oxygenated Additives. *Energies*, 16(13). <https://doi.org/10.3390/en16135153>

[4]. Akinoso, R., Olatunde, E., & Saheed, M. (2023). Measurement : Food Effects of roasting on physicochemical properties and fatty acids composition of okra seed oil. *Measurement: Food*, 9(January), 100076. <https://doi.org/10.1016/j.meafoo.2023.100076>

[5]. Al-Habaibeh, A., & Gindy, N. (2000). New approach for systematic design of condition monitoring systems for milling processes. *Journal of Materials Processing Technology*, 107(1–3), 243–251. [https://doi.org/10.1016/S0924-0136\(00\)00718-4](https://doi.org/10.1016/S0924-0136(00)00718-4)

[6]. Ashokkumar, V., Chandramughi, V. P., & Kumar, G. (2024). *Advancements in lignocellulosic biomass : A critical appraisal of fourth-generation biofuels and value-added bioproduct Advancements in lignocellulosic biomass : A critical appraisal of fourth-generation biofuels and value-added bioproduct*. February. <https://doi.org/10.1016/j.fuel.2023.130751>

[7]. Bamgboye, I. A., & Iyidiobu, B. N. (2021). Effect of Catalyst Type on the Properties of Biodiesel from Jatropha and Moringa Oil Blend. *International Research Journal of Multidisciplinary Technovation*, 3(4), 52–58. <https://doi.org/10.34256/irjmt2146>

[8]. Bashir, M. A., Wu, S., Zhu, J., Krosuri, A., Khan, M. U., & Ndeddy Aka, R. J. (2022). Recent development of advanced processing technologies for biodiesel production: A critical review. *Fuel Processing Technology*, 227. <https://doi.org/10.1016/j.fuproc.2021.107120>

[9]. Bhuiya, M. M. K., Rasul, M. G., Khan, M. M. K., Ashwath, N., & Azad, A. K. (2016). Prospects of 2nd generation biodiesel as a sustainable fuel - Part: 1 selection of feedstocks, oil extraction techniques and conversion technologies. *Renewable and Sustainable Energy Reviews*, 55, 1109–1128. <https://doi.org/10.1016/j.rser.2015.04.163>

[10]. Bojesomo, R. S., Raj, A., Elkadi, M., Ali, M. I. H., & Stephen, S. (2023). An ICP-MS study on metal content in biodiesel and bioglycerol produced from heated and unheated canola oils. *Environmental Science and Pollution Research International*, 30(54), 115064–115080. <https://doi.org/10.1007/s11356-023-30004-x>

[11]. Borowik, A., Wyszowska, J., Zaborowska, M., & Kucharski, J. (2024). *Soil Enzyme Response and Calorific Value of Zea mays Used for the Phytoremediation of Soils Contaminated with Diesel Oil*.

[12]. Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. S. (2022). Strategies to achieve a carbon neutral society: a review. In *Environmental Chemistry Letters* (Vol. 20, Issue 4). Springer International Publishing. <https://doi.org/10.1007/s10311-022-01435-8>

[13]. Dahiya, A. (2020). Biofuel conversion pathways service learning projects and case studies. In *Bioenergy: Biomass to Biofuels and Waste to Energy* (Second Edi). Elsevier. <https://doi.org/10.1016/B978-0-12-815497-7.00032-4>

[14]. Efficiency, E., & Energy, R. (2011). Straight vegetable oil as a diesel fuel? In *Biodiesel Fuels Reexamined* (Issue 2003). Anju Dahiya. <https://doi.org/10.1016/b978-0-12-407909-0.00011-0>

[15]. Gonz, P., Puentes, J. G., Moya, A. J., & Rubia, M. D. La. (2023). *applied sciences Comparative Study of the Presence of Heavy Metals in Edible Vegetable Oils*.

[16]. Haq, A., Laiq Ur Rehman, M., Rana, Q. ul A., Khan, A., Sajjad, W., Khan, H., Khan, S., Shah, A. A., Hasan, F., Ahmed, S., Islam, A., Badshah, M., Shah, T. A., Dawoud, T. M., & Bourhia, M. (2023). Production, optimization, and physicochemical characterization of biodiesel from seed oil of indigenously grown Jatropha curcas. *Frontiers in Energy Research*, 11(August), 1–14. <https://doi.org/10.3389/fenrg.2023.1225988>

[17]. Hedden, R. G. (2020). Bioheat. In *Bioenergy: Biomass to Biofuels and Waste to Energy* (Second Edi). Elsevier. <https://doi.org/10.1016/B978-0-12-815497-7.00012-9>

[18]. Hoti, K., Abdulrazaq, M. A., Polytechnic, K., & Muhammad, U. G. (2024). *Bioscene*. December.

[19]. Husaini, S., Kadire, A., Verma, R. K., & Pydimalla, M. (2025). Biodiesel production from non-edible mixed oils: a sustainable approach using jatropha, karanja and waste cooking oil. *Bulletin of Materials Science*, 48(2). <https://doi.org/10.1007/s12034-025-03414-5>

[20]. Hybrid, E., Nghia, N. T., Thi, B., Tuyen, K., Quynh, N. T., Thi, N., Thuy, T., & Nguyen, T. N. (2023). *Response Methodology Optimization and Artificial Neural Network Modeling for the Removal of Sulfamethoxazole Using*. 1–15.

[21]. Ishola, N. B., Epelle, E. I., & Betiku, E. (2024). Machine learning approaches to modeling and optimization of biodiesel production systems: State of art and future outlook. *Energy Conversion and Management: X*, 23(July), 100669. <https://doi.org/10.1016/j.ecmx.2024.100669>

[22]. Iweka, S. C., Falowo, O. A., Amosun, A. A., & Betiku, E. (2023). Optimization of microwave-assisted biodiesel production from watermelon seeds oil using thermally modified kwale anthill mud as base catalyst. *Heliyon*, 9(7), e17762. <https://doi.org/10.1016/j.heliyon.2023.e17762>

[23]. Jaspal, N., Sharma, M., Prashar, D. B., & Sharma, R. (2023). *Jatropha curcas L. : A sustainable resource for biofuel feedstock with medicinal and commercial attributes*. September. <https://doi.org/10.37446/jinagri/ra/10.3.2023.1-13>

[24]. Kafuku, G., Lee, K. T., & Mbarawa, M. (2010). The use of sulfated tin oxide as solid superacid catalyst for heterogeneous transesterification of Jatropha curcas oil. *Chemical Papers*, 64(6), 734–740. <https://doi.org/10.2478/s11696-010-0063-1>

[25]. Kumar, R., Mehta, S., & Pathak, S. R. (2018). Bioactive constituents of neem. In *Synthesis of Medicinal Agents from Plants*. Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-102071-5.00004-0>

[26]. Lams, Y. Y., Ghali, U. M., Abdulrazaq, M. A., Yakubu, A., Degm, M. A., & Agava, I. M. (2024). Aqueous Extraction and Characterization of Eucalyptus Globulus for Use as Natural Dyes. *Applied Research and Innovation*, 2(2), 23–30. <https://doi.org/10.54536/ari.v2i2.3769>

[27]. Lee, K., & Cho, H. (2024). *Comparative Analysis of Performance and Emission Characteristics of Biodiesels from Animal Fats and Vegetable Oils as Fuel for Common Rail Engines*.

[28]. Mahmoud, A., Boryo, D. E. A., & Abubakar, A. (2024). Comparative Analysis of Oil Obtained from Moringa and neem seeds. *Bima Journal OfScience and Technology*, 8(1B), 170–185. <https://doi.org/10.56892/bima.v8i1.624>

[29]. Maria Chinecherem, U., Uju, E., & Geraldine, N. (2023). Palm Oil Production for the Food and Cosmetics Industry in Africa: Ethics and Sustainability Implications. *Ethics - Scientific Research, Ethical Issues, Artificial Intelligence and Education [Working Title]*, 1–13. <https://doi.org/10.5772/intechopen.1001107>

[30]. Mcguire, J. T., Sefcik, D. A., & Lippa, K. A. (2025). *Checking the Net Contents of Packaged Goods*. December 2024.

[31]. Mini-review, A. A., Alba, S. L. De, García-gonzález, C., & Ortega, M. A. C. (2022). *Extraction Methods and Applications of Bioactive Compounds from Neem (Extraction Methods and Applications of Bioactive Compounds from Neem (Azadirachta indica) : A Mini-Review*. August 2025. <https://doi.org/10.2174/1570193X19666220707125726>

[32]. Mishra, L., Bhowmik, P. N., Anand, P., & Yantrapalli, S. (2025). A study on de-contamination of dairy wastewater using natural coagulants. *Environmental Monitoring and Assessment*, 197(6). <https://doi.org/10.1007/s10661-025-14117-z>

[33]. Musawa, B. B., Polytechnic, F., Namoda, K., & State, Z. (2024). *MODELING AND DISTRIBUTION OF NEEM (AZADIRACHTA INDICA A . JUSS) IN*. July.

[34]. Neto, F. S., Melo Neta, M., Sousa, A., Damasceno, L., Sousa, B., Medeiros, S., Melo, R., Lopes, A., Santos, J., & Rios, M. (2023). Analysis of the Fuel Properties of the Seed Shell of the Neem Plant (*Azadirachta indica*). *Processes*, 11(8). <https://doi.org/10.3390/pr11082442>

[35]. Oil, P., Journey, A., Alhaji, A. M., Almeida, E. S., Carneiro, C. R., Sodr, A., Monteiro, S., Jane, S., & Coimbra, R. (2024). *Palm Oil (Elaeis guineensis) : A Journey through Sustainability, Processing, and Utilization*.

[36]. Patil, P. D., & Deng, S. (2009). Optimization of biodiesel production from edible and non-edible vegetable oils. *Fuel*, 88(7), 1302–1306. <https://doi.org/10.1016/j.fuel.2009.01.016>

[37]. Perumal, G. (2024). Assessing biodiesel feedstocks and production techniques: a comprehensive review. *Petroleum Science and Technology*,

- 42(25), 4556–4571. <https://doi.org/10.1080/10916466.2023.2268148>
- [38]. Phase, S., Process, N., Elaeis, O., Amaral, A. R., Bernar, L. P., Ferreira, C. C., Pereira, A. M., Gomes, W., Santos, D., Pereira, L. M., Santos, M. C., Paula, F., Mendonça, N. M., Rodrigues, A., Pereira, A., Andrade, D., & Junior, S. D. (2023). *Economic Analysis of Thermal–Catalytic Process of Palm Oil (Elaeis guineensis, Jacq) and Soap Phase Residue from Neutralization Process of Palm Oil (Elaeis guineensis, Jacq)*.
- [39]. Ravindra B. Malabadi, Kiran P. Kolkar, & Raju K. Chalannavar. (2023). Industrial Cannabis sativa: Hemp oil for biodiesel production. *Magna Scientia Advanced Research and Reviews*, 9(2), 022–035. <https://doi.org/10.30574/msarr.2023.9.2.0145>
- [40]. Review, M. A., & Jamrozik, A. (2024). *Alcohols as Biofuel for a Diesel Engine with Blend*.
- [41]. Ruatpuia, J. V. L., Halder, G., Vanlalchhandama, M., Lalsangpuui, F., Boddula, R., Al-Qahtani, N., Niju, S., Mathimani, T., & Rokhum, S. L. (2024). Jatropha curcas oil a potential feedstock for biodiesel production: A critical review. *Fuel*, 370(May), 131829. <https://doi.org/10.1016/j.fuel.2024.131829>
- [42]. Sadaqat, B., Dar, M. A., Xie, R., & Sun, J. (2024). *Drawbacks of first-generation biofuels: Challenges and paradigm shifts in technology for second-and third-generation biofuels*. October. <https://doi.org/10.1016/B978-0-443-21433-2.00003-7>
- [43]. Santana, E. P., Jesus, M., Santos, J., Pires, P., Vaz-velho, M., Silva, D. P., & Ruzene, D. S. (2024). *Coconut Waste : Discovering Sustainable Approaches to Advance a Circular Economy*.
- [44]. Sharma, K., Lorenzo, J. M., Researcher, I., & Guleria, S. (2022). *Manoeuvring the physicochemical and nutritional properties of vegetable oils through blending*. October. <https://doi.org/10.1002/aocs.12661>
- [45]. Soji-adekunle, A. R., Betiku, E., Asere, A. A., Falowo, O. A., Oyewusi, T. F., & Adebeye, B. S. (2024). Optimization and modeling of the performance of compression ignition engine fired on biofuel from non-edible vegetable oils. *Cleaner Energy Systems*, 7(January), 100105. <https://doi.org/10.1016/j.cles.2023.100105>
- [46]. Tiwari, K. P., & Singh, R. N. (2024). Review on Performance and Emissions Characteristics of Compression Ignition Engine Fueling Non-Edible Vegetable Oil. *Applied Mechanics and Materials*, 919(January), 107–122. <https://doi.org/10.4028/p-cykid1>
- [47]. Tucker, N., & Kingdom, U. (2023). *Effect of Adding Nanofibers into Sunflower (Helianthus annuus) Oil on Oil Viscosity*. 21(1), 13–19. <https://doi.org/10.24323/akademik-gida.1274016>
- [48]. Zheng, F., & Cho, H. M. (2025). Study on Biodiesel Production: Feedstock Evolution, Catalyst Selection, and Influencing Factors Analysis. *Energies*, 18(10). <https://doi.org/10.3390/en18102533>