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# An Overview of Rubber Seed Oil-Based Biodiesel and Its Performance on Diesel Engine

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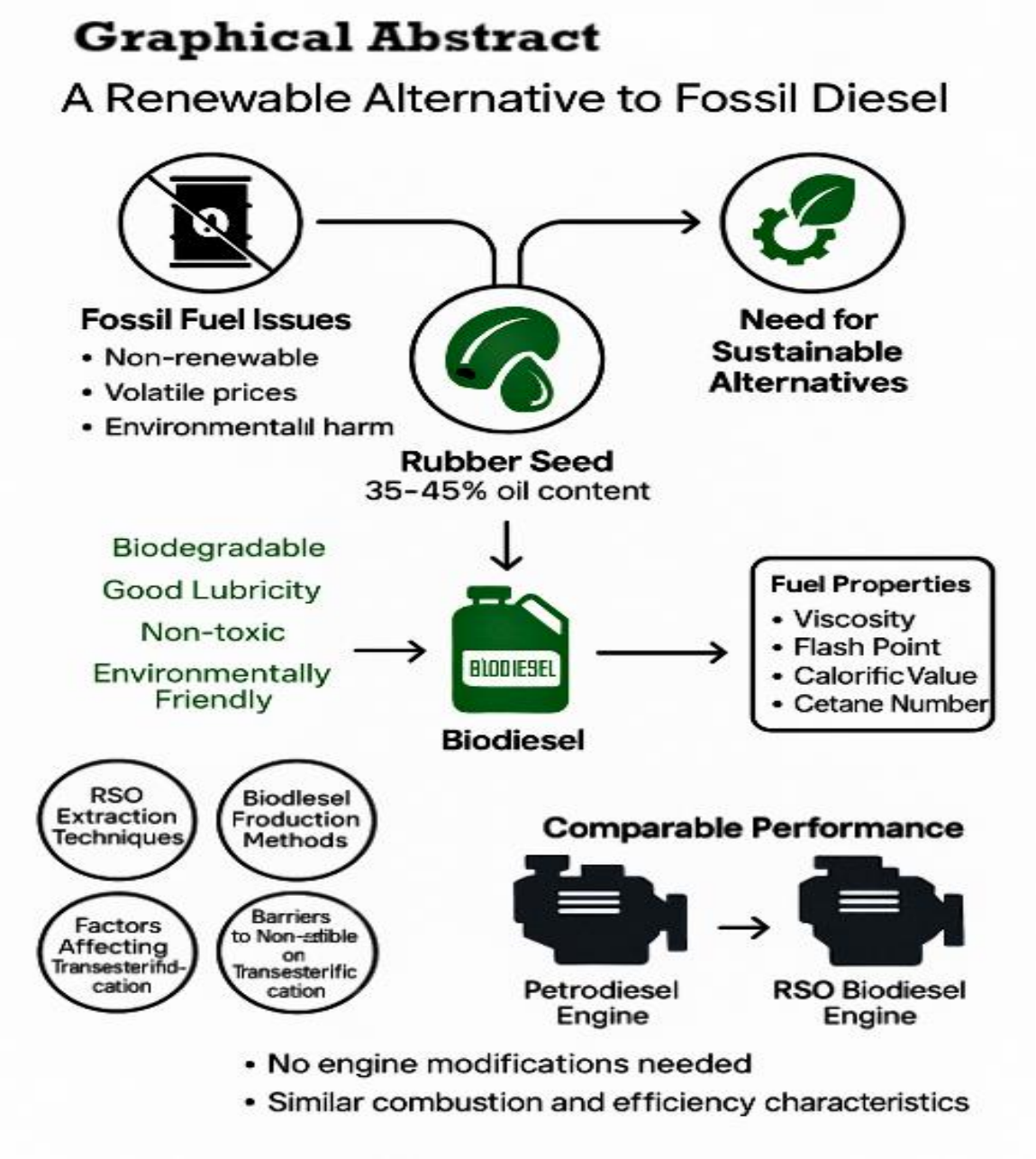
## ABSTRACT

At the moment, fossil fuels that are not renewable are used to provide the world's energy needs. Researchers worldwide have been motivated to look for renewable energies to replace fossil fuels in the future by the issues of these fuels' future unavailability, the volatility of crude oil prices, and its detrimental environmental effects. Because it shares so many characteristics with fossil diesel, in addition to being good lubricant, biodegradable, non-toxic, and environmentally friendly when used in diesel engines, biodiesel has been highlighted as a good supplement and probable replacement of fossil diesel. According to studies, rubber seeds contain 35–45 weight percent oil, making them a stronger rival to other non-edible oil-bearing plants in the biodiesel synthesis process. As a result, the current study reviewed the most recent fuel qualities of rubber seed oil (RSO) biodiesel produced over the years as well as research investigations on how rubber seed oil biodiesel performed in diesel engines. Additionally highlighted were rubber seed oil extraction techniques, biodiesel production techniques, factors influencing the transesterification of RSO, and barriers to the transesterification of non-edible oils. The characteristics of rubber seed oil biodiesel (Fatty Acid Methyl Ester), including its viscosity, flash point, calorific value, and cetane number, have been shown in numerous studies to be comparable to those of conventional petroleum diesel, making its use in internal combustion engines (ICEs) without any modifications possible. According to research on performance studies of engines using rubber seed oil biodiesel and their mixtures with petrodiesel, all of the RSO biodiesel tested had engine performance characteristics that are comparable to those of conventional engines that burn petrodiesel as fuel.

**Keywords**: Non-edible oil feedstocks; Fatty acid methyl esters (FAMEs); Transesterification kinetics; Alternative fuel combustion; Renewable energy sustainability.




**Introduction**

A multitude of industrial and food products employ plant oils that are derived from plants [1-3]. There have been hundreds of years of this practice. One of these industrial uses is the creation of biodiesel, which requires a variety of oil types. According to ASTM, biodiesel is a liquid fuel made of fatty acid alkyl ester of long-chain fatty acids obtained from vegetable oil and animal fat [4]. For the production of biodiesel, there are typically four main types of feedstocks: oil seed (vegetable oil), animal fats, algae, and various low-quality materials including used cooking oil, greases, and soap stock [5]. Oils like soybean, palm, and canola were primarily used in the creation of biodiesel on an industrial scale. However, the overuse of these vegetable oils (edible oil) causes a crisis in the ratio of food to fuel [6]. One of the biggest barriers to biodiesel's widespread commercialization is its high price. The price of the feedstock affects the cost of biodiesel by about 80% or more [5]. Recent production cost comparisons between diesel and biodiesel fuel show that fossil fuel diesel is more affordable than biodiesel [4]. Employing raw materials with a high free fatty acid content (FFA) or non-edible oils is a practical technique to lower the price of biodiesel [7-8]. The use of non-edible oil, such as rubber seed oil, as a feedstock of biodiesel production is very promising [9]. This is because the price of non-

edible oil is significantly lower than the price of edible oil, whose demand is constantly growing [10-13].

In order to produce biodiesel, non-edible oil sources like jatropha, Moringa oleifera, Pongamia pinnata, and camelina sativa have been used [14-15]. The amount of oil (35–45 Wt.%) in rubber seed portrays a better competitor to other non-edible oil-bearing plants in the production of biodiesel, in addition to the renewable nature, environmental friendliness, and simplicity of the local production of RSO biodiesel. As a result, non-edible rubber seed oils have flourished as a promising substitute to diesel fuel [4, 16]. They have almost minimal sulfur content, provide no storage issues, and have superior lubricating qualities [4, 17]. Additionally, trees that produce vegetable oils take in more carbon dioxide during photosynthesis than they release when they burn it [18]. Therefore, they fundamentally contribute to reducing the rising carbon dioxide levels in the atmosphere. Higher foreign exchange savings result from replacing diesel with renewable fuels generated in many nations, even for the largest oil exporting nations [19-21]. Therefore, this kind of project can help developing nations both solve their ecological problems and boost their economies. Vegetable oils have the potential, given their many benefits, to eventually replace petroleum-based fuels.

Rubber seed oil has been proven to be an effective biodiesel resource that satisfies the ASTM and EN criteria for biodiesel, as indicated by its physicochemical qualities and potential for use in biodiesel synthesis [6,15]. Diesel engines have been found to operate well with biodiesel made from rubber seed oil. Additionally, diesel fuel may be partially replaced by it [22]. Diesel engines can be run on a mixture of biodiesel and regular diesel fuel, which results in diesel engines running more efficiently, emitting less pollution, wearing down their components less quickly, and having lubricating oil's effects being neutral. Using biodiesel doesn't require any changes to a diesel engine, which is an intriguing feature.

The shortage of RSO biodiesel reviews in the literature is still somewhat surprising given the abundance of papers on the potential of non-edible rubber seed oil as a substitute option for biodiesel production. In actuality, Onoji *et al.* (2016) [23] and Ulfah *et al.* (2018) [24] published the only two reports on reviews of rubber seed oil-based biodiesel in the years 2016 and 2018, respectively. The work of Ulfah *et al. (*2018) is more thorough than the review by Onoji *et al*. (2016), which is quite succinct. In comparison to the two studies, this write-up is more thorough and current than the RSO biodiesel review papers previously reported. This review differs from those of Onoji *et al.* (2016) and Ulfah *et al.* (2018) because it especially highlights recent studies on the performance of rubber seed oil biodiesel on diesel engines in addition to the updated research papers on RSO biodiesel examined in this study.

Therefore, this study reviewed the fuel qualities of rubber seed oil biodiesel that had been reconstituted over the years as well as research investigations on how well it performed in diesel engines. Additionally highlighted were rubber seed oil extraction techniques, biodiesel production techniques, factors influencing the transesterification of RSO, and barriers to the transesterification of non-edible oils.

**Rubber Seed Oils**

A rubber seed weighs between 3 and 5 g on average, with the kernel making up approximately 40% of the weight, the shell around 35%, and moisture about 25% [25]. Oil content in the kernel is between 35 and 38 percent, and 57 to 62 percent of the seed cake is recovered [25]. Rubber oil and rubber seed cake are the two main products made from rubber seeds. In the rubber belt of southern Nigeria, the rubber seed typically matures and separates from the seed pod during the brief dry season between August and September [26]. Rubber seeds can be used to make two different products: oil and cake [26]. The oil has 17 to 22% saturated fatty acids and 17 to 82% unsaturated fatty acids. It is semi-drying and yellowish. Currently, no edible use is served by the oil. It could be utilized in some non-edible applications as a partial replacement for imported linseed oil because it shares some qualities with linseed oil [26]. The rotary extraction method is the most widely utilized of the three methods for extracting rubber seed oil: solvent, expeller, and rotary extraction [27]. The quality of the kernel, the degree of drying, and the volume of molasses used during processing all affect how much oil and cake may be recovered. The industry that makes soap uses rubber seed oil [27].

**Rubber seed oil extraction methods**

The seeds are reduced in size for conditioning by being dried, crushed, and milled. The milled seeds (meal) are further prepared by being scorched for 10–20 minutes at 60–70 °C in a gas-heated rotary drier [26]. Chemical and mechanical methods can be used to extract rubber seed oil from the seeds of the rubber tree. The oil could serve as a partial alternative for linseed oil because it has similar qualities [26]. According to published reports, the oil contains a significant amount of free fatty acids (FFAs), close to 80% unsaturated fatty acids (oleic, linoleic, and linolenic), and around 20% saturated fatty acids (palmitic and stearic) [28]. For RSO recovery, the following extraction techniques are available.

**Conventional method (mechanical and chemical)**

The two most popular traditional methods utilized in the extraction of oil from rubber seeds are chemical and mechanical processes. The mechanical process has a high initial cost, limited yield, but great quality [29-30]. Mechanical screw press oil expellers are said to be relatively ineffective, leaving 8–14% of the available oil in the deoiled cake [31]. Singh and Bargale (2000) advocated the use of double-stage

compression expellers to improve oil recovery [32]. Pre-treating the seed and extracting with a heated screw press head is said to improve recovery, especially when more pressure is applied [33]. N-hexane or other compatible organic solvents are frequently utilized as extractive media in the chemical technique in laboratories [17-18]. The co-extraction of unwanted oil constituents may result in inferior oil quality. The yield is impacted by a number of factors, including the boiling point of the extracting solvent, the solvent/seed ratio, milled seed size, moisture content, drying, and extraction time [34]. Gimbun *et al.* (2012) reported the extraction of RSO from 100 g of powdered rubber seeds using 250 ml of n-hexane under process conditions of 4 h at 60 °C [35]. The hexane was then evaporated from the oil/hexane mixture using a vacuum and a temperature of 60 °C.

**Gas-assisted mechanical expression method**

This approach, known as Gas Assisted Mechanical Expression (GAME), entails dissolving supercritical $CO_2$ fluid into the powdered seeds and then compressing it with a screw [36]. This made it possible to apply less pressure while yet retaining a higher yield without sacrificing quality [36]. Before pressing, $CO_2$ is dissolved in the oil present in the seeds as part of the GAME process. The oil/$CO_2$ mixture is extracted from the seeds after equilibration. For cocoa, it has been demonstrated that during pressing, the dissolved $CO_2$ displaces some of the oil [37]. The results showed that the liquid content of conventional and GAME press cakes is the same at the same effective mechanical pressure (absolute mechanical pressure minus the real $CO_2$ pressure) [37]. When compared to the conventional cake, the oil content of the GAME press cake is reduced by the same amount since the liquid is saturated with $CO_2$ (up to 30 wt% $CO_2$). With greater $CO_2$ solubility in the oil, this effect's magnitude increases [38]. Additionally, the oil's viscosity is reduced by an order of magnitude due to the dissolved $CO_2$, which accelerates the pressing process. After pressing, depressurization makes it simple to remove $CO_2$ from the cake and oil. Additional oil is taken from the cake during depressurization by entrainment in the gas flow [38].

The advantages of GAME include:

1. Mechanical pressing can produce higher yields while using less pressure (50 MPa as opposed to 100 MPa).
2. Compared to supercritical extraction, lower $CO_2$ pressure is necessary (10 MPa compared to 45-70 MPa).
3. Compared to supercritical extraction, substantially less $CO_2$ is needed (around 1 kg $CO_2$ per kg oil compared to 100 kg $CO_2$ per kg oil).
4. The products are almost completely solvent-free, with no negative health effects on consumers.
5. According to various publications, $CO_2$ has a sterilizing effect under the settings used.

**Ultrasonic-assisted method**

The best way to release oils from seeds, kernels, and fruits is through ultrasonic extraction. Using ultrasound to create rapid solvent movement, ultrasonic-assisted extraction (UAE) is a quick and efficient extraction method. This accelerates extraction by increasing mass transfer speed [39]. When small bubbles develop and burst, a tremendous amount of energy, pressure, and mechanical shear are released. The seeds' cell tissues are broken down by the ultrasonic, which extracts the oil into the solvent [40]. This method's main benefits are its quick extraction time and minimal solvent usage. In a conventional ultrasonic-assisted procedure, a known gram of milled seed powder is placed in an Erlenmeyer flask along with an extraction solvent, and the flask is then submerged in a sonication bath for extraction. The extract is taken from the vessel when extraction is finished and filtered with filter paper in a vacuum. Drying chemicals like anhydrous sodium can then be used to dehydrate the seed filtrate [39].

**Microwave-assisted method**

With frequencies ranging from 300 MHz to 300 GHz, microwaves are electromagnetic energy. The waves that carry this energy enter biomaterials and interact with molecules to produce heat [41]. Localized heating is caused by microwaves' selective interactions with the existing free water molecules. As a result, the temperature quickly rises to the point where water begins to boil. Due to the fast expansion that results, their walls eventually break [42]. Low specific heat exists in lipids. They thereby become vulnerable to harmful radiation [43]. As a result, the seed would develop permanent pores, increasing output [44]. The main benefit of using a microwave is efficient heating. Microwave Assisted Extraction (MAE) has demonstrated the ability to shorten extraction times while minimizing environmental effect by generating less $CO_2$ and using a small portion of the energy needed in conventional extraction procedures [45-46]. This technique greatly improves the extraction's effectiveness [46]. As a result, microwave-assisted extraction is often affordable [9]. The majority of chemicals are protected from degrading processes by the brief microwave exposure time [47]. Higher oil yields, higher oil quality, and better extraction rates suggest that a continuous microwave system would be practical for a wider range of oil-bearing seeds [48]. As a result, it may be assumed that it is a feasible method for obtaining oil from the seeds of *Pongamia pinnata.* The tree species *Pongamia pinnata*, whose oil is non-edible, is widely distributed in southern India. The *pongamia pinnata* is a crucial sustainable feedstock for manufacturing biodiesel due to the rise in demand for fuels and strain on edible oils, as well as having benefits including the ability to be grown in non-fertile and waste land [49].

**Aqueous Extraction Processing**

Aqueous extractions (AEP) for seeds have the fundamental advantage that water can be used as a

solvent instead of more harmful organic solvents like hexane. In solvent extractions, the seed substrate's oil dissolves in the solvent phase [13]. The organic solvent is then evaporated, recovering the oil in the process. Solid residue, protein-rich skim, lipid-rich cream, and free oil are the usual fractions that are separated from oil using AEP [50]. Demulsifying the cream is one of the additional procedures required to release free oil as a result. The most ideal extraction would be one that extracts the most oil for its own sake, as these processes can add considerable expenses to oil recovery. Consequently, the best predictor of recovered free oil is not usually the extraction yield. AEP typically yields less than those achieved with organic solvents, regardless of matrix; nevertheless, several research studies have shown competitive recovery yields of up to 96% [49, 51]. Pre-treatments are frequently used before aqueous extractions, and they all work to break down or soften the seed matrix in order to maximize oil recovery. For instance, roasting seeds can increase yields because heat can break down the cell walls of the substrate and enhance oil release [52]. Thus, a 35% (w/w) oil extraction yield was achieved utilizing the ideal roasting temperature and duration for wild almonds [51]. Prior to aqueous extraction, flaking and extrusion may also encourage enhanced cell breakdown, enabling improved water penetration and the release of contained chemicals. Extruded full fat soybean flakes (68%) produced much higher oil extraction yields for the aqueous extraction of soybeans than untreated soybean flakes (60%) did [53]. It has been demonstrated that several pretreatments specifically enhance free oil recovery. The creation of a thinner cream layer and an increase in the free oil yields from 19 to 83% were the results of pretreating flaxseed kernels with 0.3 M citric acid and drying them at 70 °C for 1 h before aqueous extraction. The capacity of the acid treatment to modify protein characteristics, which resulted in the coalescence of oil bodies and size decrease in protein bodies, was connected to the large improvement in free oil recovery [54]. Aqueous oil extraction can also be done using a variety of tools. Sunflower seeds were processed in a blender instead of a twin-screw extruder, which resulted in a 35% higher oil yield [55].

**Aqueous enzymatic method**

Enzymes are effective extractive media due to their great specificity and efficiency. The seed kernels' cell walls are hydrolyzed and broken, releasing the oil component. This approach is deemed to be environmentally friendly, low initial cost, and simple to turn the de-oiled cake into livestock feeds because no solvent is used [34].

All areas of food processing regularly use enzymes, and adding them to aqueous oil extraction has various benefits. The cotyledon's cell walls, which are formed of cellulose, hemicellulose, lignin, and pectin, make it challenging to release oil from it [34]. Thus, to break down the cell wall and promote oil release, seeds can be treated with substrate-specific enzymes such carbohydrases (i.e., cellulase, hemicellulase, and pectinase). Protease is used to hydrolyze proteins in the cell membrane, which improves the effectiveness of seed extraction [56-57]. Enzyme treatment does not leave behind solvent residues, happens at low temperatures, and is environmentally benign [34, 56-57]. Enzymatic processes have less of an influence on global warming, acidification, eutrophication, ozone generation, and energy consumption, according to life cycle analyses (LCA) on their use in the food, feed, and pharmaceutical industries [58] (Jegannathan & Nielsen, 2009). Although the cost of enzymes can be high, they may be offset by higher extraction yields or enzyme recycling [56, 59]. As with any process, getting optimal extraction yields requires parameter optimization. While various factors, such as the kind of enzyme (for example, proteases vs. carbohydrases), affect the pH of enzymes, it is essential to set the pH far from the isoelectric pH (pI) of seed proteins. The insoluble nature of proteins at their pI can make oil extraction difficult [34, 60-62]. Another crucial factor to take into account while utilizing enzymes is the temperature, with 45 to 55 °C being the normal optimal range for enzymatic hydrolysis. Enzymes may lose their ability to catalyze hydrolysis if temperatures are too high. But low temperatures can delay the rate at which oils are extracted and the rate at which enzymes respond [34, 60].

**Physicochemical properties of rubber seed oil**

In the literature, many researchers' reports on the physicochemical properties of RSO are described [16]. It is possible to evaluate the RSO as a source of potential industrial feedstock for producing biodiesel and other uses by recognizing these features. Stearic (C18:0), palmitic (C16:0), oleic (C18:1), linoleic (C18:2), and linolenic (C18:3) are the fatty acids that are most frequently recorded [63-64]. Other acids in smaller concentrations could also be present. These publications claim that unsaturated fatty acids, particularly polyunsaturated acids, make up the majority of RSO [64]. Depending on the methodologies used for analysis, the location of the rubber tree, and the extraction processes, the values reported by researchers may differ slightly. However, numerous non-edible vegetable oils described in literature have similar qualities [65].

**Biodiesel production methods**

The production of biodiesel can be done in a number of ways, including transesterification, pre-treatment, pyrolysis, and water emulsion, among others. The primary goals of producing biodiesel are to increase the volatility and decrease the viscosity of the bio-oil.

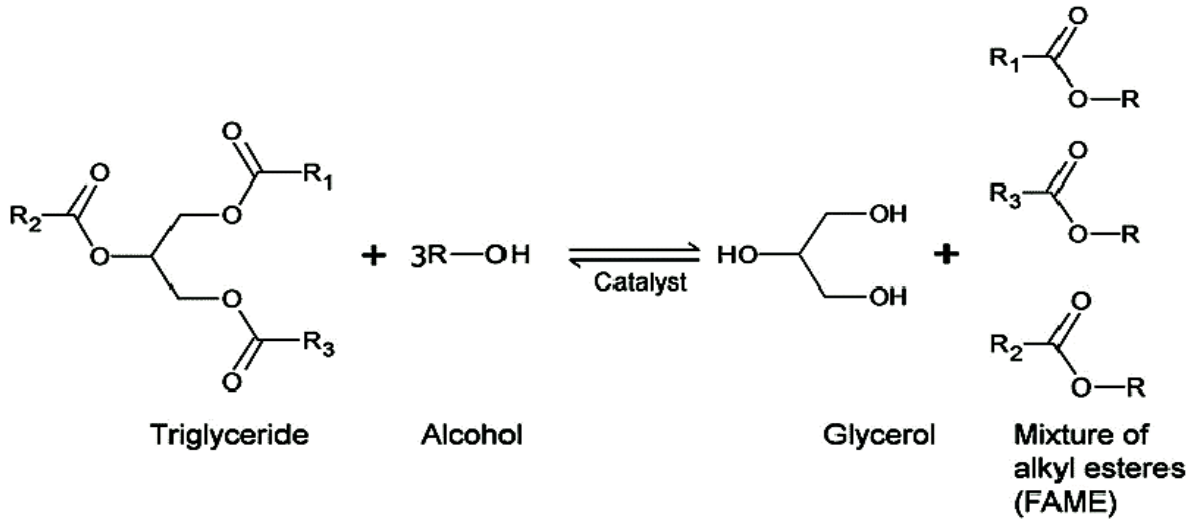
**Pretreatment Methods**

Pretreatment refers to the applied steps necessary in the biodiesel process to treat feedstocks before they are transformed into biodiesel [66]. These phases usually include removing elements that have a negative impact on the manufacture of biodiesel, such

as water, gums, suspended particles, polymers, and especially FFAs [67]. When alkaline transesterification occurs, water typically causes the formation of higher concentrations of soaps, reacts with sodium methylate, an alkaline catalyst, to produce methanol and sodium hydroxide, and also causes the equilibrium reaction to shift toward hydrolysis when acid catalysis is present [67]. The soaps may freeze or harden and block the equipment, causing downtime (downtime). One pretreatment technique involves combining caustic soda and FFAs; nevertheless, this pretreatment technique will result in significant yield reductions [68]. However, since soaps don't form as a result of the acid pretreatment, there will be little yield loss. The destruction of the catalyst and potential effects on the phase separation of the oil/glycerol phases are two additional detrimental effects of polymers, gums, and particles in oil feedstocks on the biodiesel manufacturing process [69]. A variety of pretreatment techniques have been adopted by the biodiesel industry worldwide, including liquid acid treatment (pretreatment by esterification of FFAs with a liquid acid catalyst), distillation (removal of FFAs by distillation), blending (combining low FFAs feedstock with higher FFAs feedstock), glycerolysis (glycerol reaction with FFAs), acid esterification with solid catalysts (lower FFA with ion exchange), removal of FFA with [66].

**Transesterification**

Triglycerides (fats) found in oils are utilized as feedstocks in the transesterification process to create viable biodiesel. Because of its significantly lower viscosity, transesterified biodiesel can take the place of petroleum diesel in diesel engines [70]. The process of making biodiesel through transesterification of triglycerides, which make up the majority of vegetable oils and animal fats, is used on an industrial scale throughout the world. Because methanol is typically the least expensive alcohol, methyl esters are the most prevalent type of esters [70]. Bases, acids, and enzymes work together to catalyze the reaction, which can happen at either low or high temperatures. Glycerol is a byproduct of the reaction that produces biodiesel, which is described as the methyl esters of fatty acids that are produced [71]. The overall equation and the process for producing biodiesel from the transesterification reaction are shown in Scheme 1.




Scheme 1: Transesterification of vegetable oil for biodiesel production [72]

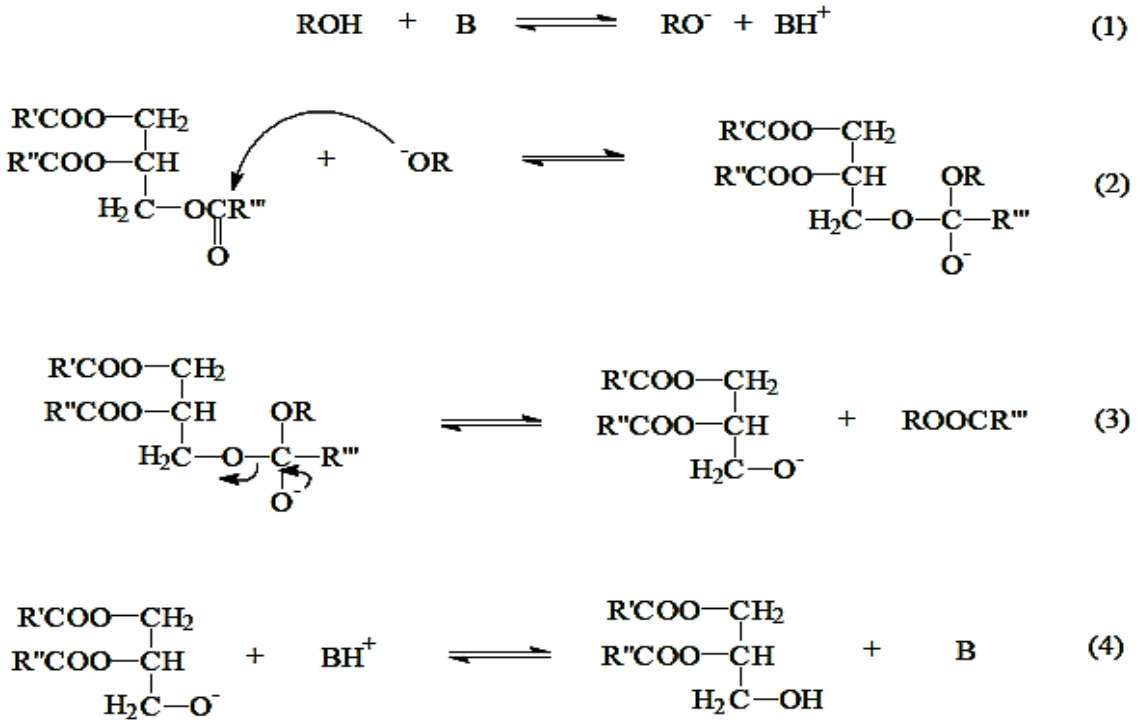
The intermediates produced during this reaction are di- and mono-acyl-glycerol. The graphic below shows the relationship between the conversion of alkyl esters and the reaction time's intermediate products in qualitative terms [73]. Equation 1 gives a detailed description of how FAMEs biodiesel is produced. Four steps are required to complete the transesterification reaction. Mixing the catalyst, usually a powerful base like NaOH or KOH, with the alcohol for the reaction is the initial step. The transesterification reaction then occurs as a result of the reaction between the fatty acid and the alcohol/catalyst [74].

Methanol is combined with a potent base, such as sodium or potassium hydroxide, to create the catalyst. The NaOH splits into $Na^+$ and $OH^-$ ions during the process. In order to create water, the OH- removes the hydrogen from methanol, leaving the CH3O- free for reaction [74]. Ideally, methanol will be completely dry. Water is created when the OH- ion interacts with

the H+ ion. Free fatty acids (fatty acids that aren't triglycerides) and water are more likely to have an unintended side reaction that results in soap [74]. Alcohol still has to be present and merely serves as a catalyst in enzymatic activities (known as lipases). Lipases are expensive, slow, and produce low yields compared to chemical catalysts [75-76]. As soon as the catalyst is ready, the triglyceride will react with 3 mols of methanol, hence extra methanol must be added to the reaction to achieve a complete one. In contrast, the $CH_3$ group interacts with the free fatty acid to generate the fatty acid methyl ester when the three connected carbons with hydrogen combine with OH- ions [77]. These are some descriptions of the transesterification catalysts:

**Base-Catalyzed Processes**

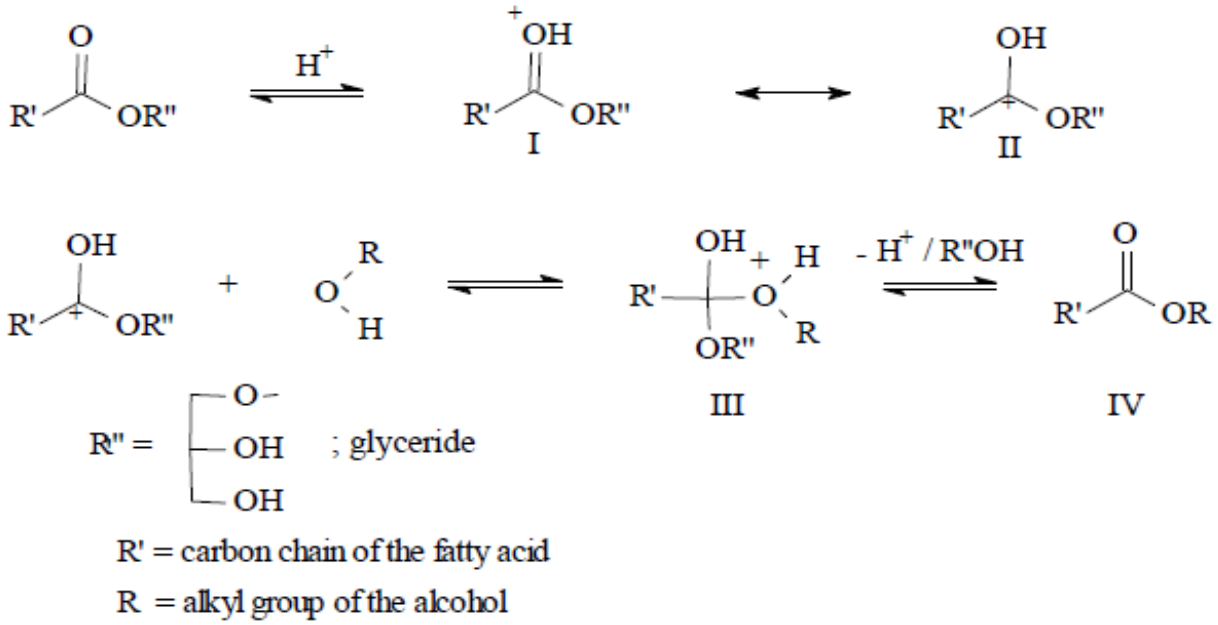
Plant oil transesterification that is base-catalyzed proceeds more quickly than an acid-catalyzed process. Due to this and the fact that base catalysts, such as sodium or potassium carbonates as well as alkaline metal alkoxides and hydroxides, are less corrosive than acidic compounds, industrial processes typically favor them [78]. In Scheme 2, the mechanism for base-catalyzed transesterification of vegetable oils is depicted. The base reacts with the alcohol in the first stage (Eq. 1) to form an alkoxide and the protonated catalyst. A tetrahedral intermediate is produced by the alkoxide's nucleophilic assault on the triglyceride's carbonyl group in equation (2), which leads to the formation of the alkyl ester and the corresponding anion of the diglyceride (Eq. 3). By deprotonating the catalyst, the latter regenerates the active species (Eq. 4), which is then prepared to interact with a second molecule of alcohol to initiate a new catalytic cycle. The same mechanism transforms diglycerides and monoglycerides into an amalgam of alkyl esters and glycerol. The most effective catalysts are alkaline metal alkoxides (such as $CH_3ONa$ for methanolysis), which offer extremely high yields (> 98%) in a short amount of time (30 min) even when used at low molar concentrations (0.5 mol%). However, they are incompatible with common industrial procedures since they require the absence of water [79]. Although less active than metal alkoxides, alkaline metal hydroxides (KOH and NaOH) are less expensive. However, by just raising the catalyst concentration to 1 or 2 mol%, they can provide the same high conversions of vegetable oils [75]. However, even when an alcohol/oil mixture devoid of water is utilized, the interaction between the hydroxide and the alcohol still results in the production of some water in the system. Water causes some of the generated ester to hydrolyze, which leads to the creation of soap (Scheme 7). Due to the creation of emulsions, this unfavorable saponification reaction decreases ester yields and makes recovering glycerol much more difficult [80]. When applied at a concentration of 2 or 3 mol%, potassium carbonate produces large yields of fatty acid alkyl esters while reducing the production of soap. The creation of bicarbonate rather than water (Scheme 8), which does not hydrolyze the esters, can account for this [81].




**Scheme 2.** Mechanism of the base-catalyzed transesterification of vegetable oils [78]

**Acid-Catalyzed Processes**

Brnsted acids, sulfonic and sulfuric acids in particular, are preferred for catalyzing the transesterification process [82]. These catalysts provide extremely high yields of alkyl esters, but the reactions take a long time to complete, generally taking more than three hours and temperatures above 100 °C [82]. One of the primary elements that affects transesterification is the molar ratio of the alcohol to the vegetable oil. The creation of the products is favored by an excess of alcohol [78]. The recovery of the glycerol is complicated by too much alcohol, on the other hand, therefore the appropriate alcohol to oil ratio must be determined empirically while taking into account each distinct procedure. Scheme 3 illustrates the mechanism of a monoglyceride's acid-catalyzed transesterification of vegetable oils. It can, however, be expanded to include di- and triglycerides. The protonation of the ester's carbonyl group results in the carbocation II, which, following the alcohol's nucleophilic assault, yields the tetrahedral intermediate III. This intermediate then consumes glycerol to create the new ester IV and regenerates the catalyst H+. This mechanism states that the reaction between the carbocation II and the water present in the reaction mixture can result in the formation of carboxylic acids. In order to prevent the competitive synthesis of carboxylic acids that lower the yields of alkyl esters, this recommends that an acid-catalyzed transesterification should be performed in the absence of water [78].




**Scheme 3.** Mechanism of the acid-catalyzed transesterification of vegetable oils [78]

**Lipase-Catalyzed Processes**

It has been revealed that lipases can also be utilized as a catalyst in transesterification and esterification reactions, in addition to other reactions that are used to catalyze, such as the hydrolysis of glycerol, alcoholysis, and acidolysis [83]. Hydrolytic enzymes have been used a lot in organic synthesis because they are readily available and easy to handle [84]. They are reasonably stable, do not require any coenzymes, and frequently withstand organic solvents. They are useful tools because of their capacity for regio- and particularly enantioselective synthesis [85]. In comparison to base-catalyzed reaction systems, the reaction yields and the reaction durations are still unfavorable. The efficient transesterification of triglycerides can also be facilitated by the extracellular and intracellular lipases [86]. To address some of its drawbacks, additional research into enzyme-catalyzed transesterification processes is required. The common elements of these investigations include adjusting the reaction parameters (solvent, temperature, pH, kind of microbe that produces the enzyme, etc.) to develop characteristics that are ideal for an industrial use [87]. Figure 1 depicts the general enzyme transesterification biodiesel synthesis process.

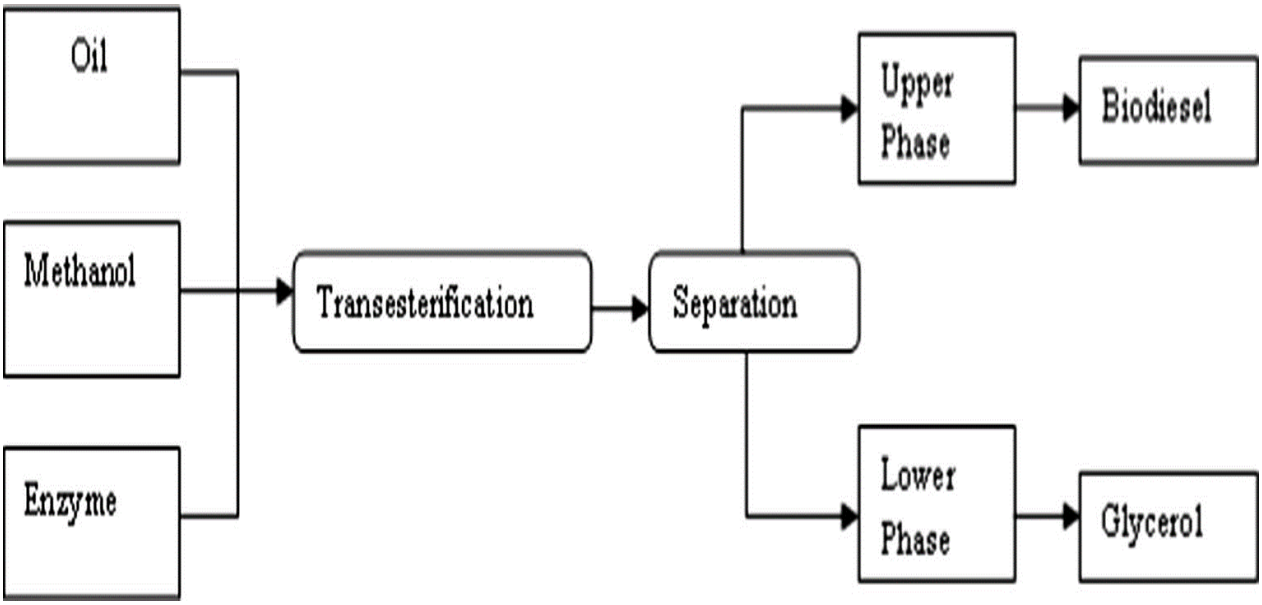



Fig. 1: General biodiesel production process of enzyme transesterification [83]

**Ultrasound-assisted technique**

The process of transmitting an oscillating sound pressure wave at a frequency higher than the upper limit of the human perceptual range is known as ultrasound [88]. The range of ultrasound frequencies is 20 kHz to 1 MHz, with corresponding liquid acoustic wavelengths of about 100-0.15 mm. Due to ultrasound, the chemical privilege accelerates mass transfer and chemical reactions, resulting in faster reaction times and less expensive reagents [88]. Escalation waves and compression waves generated by sound propagating through the liquid result in the formation of an aerosol comprising solvent, solute vapor, and previously dissolved gases [83]. The high mass transfer rates that result from the development of a microemulsion by ultrasonic cavitations cause bubbles to grow and then recompress as a result of this occurrence. Its use has been promoted as a way to get around the inherent problems of the standard transesterification process's poor batch reaction rates and time-consuming phase separation [83].

**Microwave-assisted technique**

Many organic syntheses use microwaves, which are electromagnetic waves with frequency ranging from 0.3 GHz to 300 GHz [83]. The primary components of the microwave heating method are ionic conduction and dipolar polarization. the attempt by polar molecules like methanol and water to realign themselves under an ever-changing electric field, known as dipolar polarization. It works against the force between their molecules. Polar molecules collide and lose absorbed energy as heat when they are not kept in phase with the applied field. In ionic conduction, heat is produced as the motion of the material's ions slows, changes direction, and collides with one another in an oscillating electromagnetic field [89]. High frequency causes the field to oscillate very quickly, though. Due to the short response time and significant intermolecular interaction in this situation, the motions of polar molecules cease to move. The microwave at a frequency of 2.45 GHz is employed in residential and laboratory synthesis because it produces no heat.

Organic synthesis is one of the many applications for microwave irradiation. Polar molecules selectively absorb microwave energy, but nonpolar molecules are inert to the microwave dielectric loss. As a result, chemical reactions are accelerated. Additionally, microwave-assisted chemical synthesis has the advantages of quick reactions, excellent product purity, increased yields, and improved energy economy [83]. It has been extensively researched how to use the microwave-assisted transesterification process to produce biodiesel from vegetable oils. It was determined that microwave-assisted practice is more energy-efficient, limits the impacts on enzymes, and produces more biodiesel than conventional heating [90]. Due to their simple accessibility, low cost, and noncorrosive environment, magnesium and calcium oxides have been tested as solid base catalysts. Owing to its insolubility non methanol, strontium oxide has garnered interest among alkaline-earth metal oxides as a heterogeneous catalyst [91]. At a relatively sensible temperature of about 65 °C, a yield of 95% has been achieved in 30 minutes. The creation of a variety of zinc and aluminum oxides for use as a heterogeneous catalyst has led to high conversion (98.3%) of biodiesel and glycerol with more than 98% purity [92]. Since the composition of hydrotalcite allows for the adjustment of both its acidic and basic properties, it is an essential kind of catalyst that is extensively tested for the generation of

biodiesel. To create high yield (87.3%) biodiesel from vegetable oils, an exceptional earth metal oxide ($Eu_2O_3$) has been used as a solid super base heterogeneous catalyst [93]. It has been discovered that the synthesis of biodiesel works extremely well with alumina that has been loaded with diverse chemicals. Biodiesel made from vegetable oils will yield 95% more when $Al_2O_3$ is added. For the production of biodiesel, zeolites have recently been tested as a potential heterogeneous catalyst [75]. To achieve a superior conversion of methyl esters, yield of 94.6%, various zeolites and metals have been tested as transesterification catalysts. In a supercritical process carried out in a retort without a catalyst and under conditions of high temperature and high pressure, biodiesel can be produced. The method offers benefits like improved phase solubility, circumventing mass transfer constraints, high reaction rate, trouble-free separation, and purification of the produced products. Even with moisture and FFA present, the procedure is still permissible [94-95].
Other contemporary methods and a variety of catalysts are employed in the production of biodiesel from vegetable oils, including the supercritical process, the hydrotalcite/layered double hydroxide (LDH)-derived catalysts, the solid superbase catalyst, the alumina loaded with various compounds, the ultrasound-assisted method, and the microwave-assisted method.

**Factors Influencing the Transesterification of Rubber Seed Oil (RSO) for Biodiesel Production**
The transesterification of rubber seed oil (RSO) for biodiesel production is influenced by multiple factors that affect reaction efficiency, biodiesel yield, and overall process viability. Key parameters considered in this study include the free fatty acid (FFA) content of RSO, the alcohol-to-oil molar ratio, catalyst concentration, reaction temperature, and challenges associated with non-edible oils.

**Free Fatty Acid (FFA) Content of RSO**
RSO is characterized by a high FFA content, ranging from 23.471% to 45 wt% [16, 49, 96]. When using a homogeneous base catalyst for transesterification, reducing the FFA content is critical to avoid soap formation and downstream processing challenges [97]. To lower the FFA to below 1 wt%, the oil is typically esterified with alcohol using a homogeneous acid catalyst such as H2SO4. Among the reaction parameters, catalyst concentration and the alcohol-to-oil molar ratio exert the most significant influence compared to temperature and time [98].

**Alcohol-to-Oil Molar Ratio**
The molar ratio of alcohol to oil significantly impacts biodiesel yield. A low molar ratio impairs the conversion of triglycerides to fatty acid methyl esters (FAME), while an excessively high ratio complicates separation and increases production costs [97]. Since transesterification is a reversible reaction, excess alcohol is required to drive the reaction toward product formation. However, the hydroxyl group in methanol can promote emulsification between glycerol and biodiesel, facilitating reverse reactions that reduce yield [99]. To achieve a biodiesel yield of 98% (w/w), an optimal methanol-to-oil ratio of 6:1 is generally required for alkaline catalysts, which stabilizes fatty acid-glycerol chains [76]. Musa et al. (2016) reported that the optimal molar ratios for methanol and ethanol were 6:1 and 9:1, respectively, with biodiesel yield increasing linearly until reaching an optimal point beyond which it declines [76]. Excess alcohol also complicates the recovery of glycerol and methanol, as noted in studies on alkaline catalysts like KOH, which have reported biodiesel yields of 75–96.8% wt.% at a 6:1 alcohol/oil ratio [100]. Ahmad et al. (2014) highlighted that the alcohol/oil molar ratio is crucial up to a threshold beyond which additional methanol has no further impact on yield but increases downstream processing complexity [101].

**Catalyst Concentration**
Catalysts, whether alkaline, acidic, or enzymatic, play a crucial role in achieving high biodiesel yields. Excess catalyst use can lead to emulsions with high viscosity, making biodiesel separation challenging and promoting saponification, which reduces biodiesel production [102]. Commonly used alkaline catalysts include NaOH and KOH, while recent research has explored heterogeneous catalysts due to their recyclability and reusability [103]. Gimbun et al. investigated the use of CaO derived from activated cement clinker for RSO transesterification, achieving a 92.3% conversion at a 6% (w/w) catalyst concentration [103]. Similarly, Zamberi and Ani (2016) reported an optimal catalyst concentration of 9% (w/w) using CaO from waste cockle shells, yielding 88.06% biodiesel. Beyond this concentration, yields decline [104]. RSO biodiesel yield generally increases with catalyst concentration up to an optimal level, after which further increases lead to diminishing returns. Optimization of catalyst weight, calcination temperature, and reaction time is essential [97]. The visual appearance of RSO biodiesel is influenced by catalyst concentration, with excessive amounts leading to a darker product [97, 105].

**Reaction Temperature**
Reaction temperature significantly affects biodiesel yield and reaction kinetics. Increasing the temperature enhances reaction rates, reduces oil viscosity, and improves the mixing of oil and alcohol, thereby facilitating glycerol separation [97]. However, excessive temperature can trigger side reactions such as triglyceride saponification and methyl ester hydrolysis, leading to biodiesel yield reductions [99, 101]. Gimbun *et al.* (2013) examined RSO transesterification within a temperature range of 40–70°C, maintaining other parameters constant [103]. Their findings indicated that transesterification

efficiency improves at higher temperatures, with an optimal temperature of 65°C when using a limestone-based catalyst. Beyond 65°C, conversion rates stagnate, and at 70°C, they decline due to methanol evaporation, which disrupts the reaction balance.

**Challenges in the Transesterification of Non-Edible Oils**

Non-edible oils, including RSO, typically contain high FFA levels (2.53–22% by weight), rendering alkaline transesterification impractical due to soap formation, increased catalyst consumption, and reduced catalyst efficiency [106]. Soap formation elevates viscosity and causes gel and foam production, complicating biodiesel-glycerol separation [75]. Various strategies have been explored to address this issue, including multi-stage reactions (two- or three-stage processes), acid- and alkaline-catalyzed esterification and transesterification, enzymatic catalysis, and supercritical methanol techniques [107]. Enzymatic transesterification is unaffected by water content in the feedstock and occurs at the aqueous-oil phase interface, resulting in high-purity alkyl esters that are easy to separate [108]. Supercritical transesterification, performed at elevated temperature and pressure, can accommodate high water content without catalyst deactivation and significantly reduces reaction time [109-111]. By optimizing these factors, the efficiency and feasibility of RSO transesterification for biodiesel production can be improved, making it a viable alternative fuel source.

**Up to date overview of rubber seed oil biodiesel synthesized over the years**

Numerous studies have looked into the manufacturing of biodiesel with a high FFA content and fuel-quality [4, 112]. According to the results of multiple studies, the commercially available alkaline catalyst transesterification technique is unable to transesterify feedstocks with high FFA levels. The FFAs and alkaline catalysts react to generate soap, which keeps the glycerin and ester from separating. To transform the high FFA oils into their esters, Ramadhas *et al.* (2005) created a two-step transesterification procedure [8]. The oil's FFA level is lowered to under 2% in the first stage, which is acid catalyzed transesterification. The first step's byproducts are converted to mono-esters and glycerol by the alkaline catalyst transesterification process. In each step, the effects of the alcohol to oil molar ratio, catalyst quantity, reaction temperature, and reaction time are examined. The substance darkens when sulfuric acid is added in excess. Additionally, it has been discovered that the molar ratio of alcohol to oil has a significant impact on conversion efficiency. The alkaline catalyzed esterification process is more likely to be finished in less than 30 minutes when the molar ratio is 6:1. The reaction temperature (45 °C) is where the most ester conversion occurs. Biodiesel has a viscosity that is closer to that of diesel. Although biodiesel has a slightly lower calorific value than diesel (approximately 130 °C), it has a higher flash point than diesel. Since it uses inexpensive, unrefined, non-edible oils, this two-step esterification process lowers the cost of producing biodiesel overall. According to the investigation conducted here, biodiesel made from raw rubber seed oil is a great substitute for diesel. A longer run and wear examination of an engine powered by biodiesel, as well as other fuel property measurements, need to be studied further.

In a related study, Sugebo *et al.* (2021) optimized the oil yield from rubber seeds, determined the physicochemical characteristics of the oil, and produced biodiesel from the optimized oil [113]. Using the core composite design of the response surface methodology, the oil was extracted using a solvent extraction technique. A two-step, acid-base catalyzed transesterification using a 6:1 molar ratio of methanol to oil was used to create the biodiesel. This process took 90 minutes at 60 °C. Gas chromatography-mass spectrometry was used to determine the fatty acid composition of the biodiesel. With a solvent to solute ratio of 9:1 and an extraction time of 8 hours at 95 °C, the highest oil yield of 61.3 wt% was achieved. A maximum yield of 81.55 wt% of biodiesel was produced from the oil due to its favorable physicochemical characteristics for the manufacturing of the fuel. The ASTM6751 and EN590 standards were met by the fuel qualities of the biodiesel made from rubber seed oil. 83.4% unsaturated and 16.1% saturated fatty acids made up the synthetic biodiesel. The oxidation stability of the fuel may be lessened by the presence of unsaturated fatty acids. The current research suggests that rubber seed might be regarded as a crucial feedstock for biodiesel. For the transesterification reaction in the manufacturing of biodiesel fuel, Le *et al.* (2018) developed a new technique using the co-solvent of FAMEs [114]. Using 34% of the oil's FAMEs as the co-solvent, the crude RSO was transesterified after being esterified. With a MeOH/oil molar ratio of 4.5:1 and 1 wt% KOH, the excellent quality of BDF (99.2%) was produced at 40 °C in 30 minutes. The EN 14214 and JIS K2390 standards were met by the physicochemical characteristics of the BDF from RSO. In terms of both solvent consumption and the reaction rate of transesterification, the approach using a co-solvent of FAMEs provides a number of advantages. Additionally, choosing the appropriate FAMEs as a co-solvent before the transesterification offers the opportunity to modify the physicochemical features of BDF. The procedure is akin to how BDF is made for the market and mixed with other types of FAMEs.

According to Kawashima *et al.* (2008; 2009), heterogeneous base catalysts have the advantages of being reusable, noncorrosive, showing greater tolerance to water and free fatty acids (FFAs) in feedstock, improving biodiesel yield and purity, having a simpler purification process for glycerol, and

being simple to separate from the biodiesel product [115-116]. One of the most used heterogeneous base catalysts for the transesterification of vegetable oil is calcium oxide (CaO) [117]. The use of CaO as a solid base catalyst in the production of biodiesel offers numerous benefits, including increased activity, gentle reaction conditions, reusability, and low cost [118]. The usage of nanopowdered CaO has a number of difficulties since it is difficult to obtain and requires a lot of energy to make. In addition, catalyst recovery or separation will be difficult for nanoparticle. Gimbun *et al.* (2012) highlighted the possibility of a limestone-based catalyst for transesterification of high free fatty acid (FFA) rubber seed oil (RSO) [35]. Clinker, which is pre-calcinated limestone, was transesterified and activated with methanol while being continuously stirred at reflux. By combining internal x-ray diffraction with x-ray fluorescence (XRF), the mineral composition of the catalyst was examined (XRD). Both microwave extraction and soxhlet extraction utilizing hexane as the solvent were used to get the rubber seed oil. Gas chromatography mass spectrometry was used to calculate the FFA content and the fatty acid methyl ester content (GC-MS). The outcomes demonstrated an effective conversion of high FFA rubber seed oil to biodiesel (up to 96.9%). The findings imply that the catalyst used in this study is not adversely affected by moisture and free fatty acids and may be regenerated extremely easily without suffering a major loss in activity. The catalyst activated at 700°C, with a catalyst loading of 5 weight percent, a methanol to oil molar ratio of 5:1, a reaction temperature of 65°C, and a reaction period of 4 hours, produced the greatest conversion of 96.9%. The biodiesel produced in this experiment is within the parameters specified by the American standard test technique (ASTM D6751). Likewise, Omorogbe *et al.* (2013) used various catalysts, including sodium hydroxide (1), sodium metal (2), sulphuric acid (3), phosphoric acid (4), clay acid (5), and alkaline (6) activated, to prepare biodiesel from crude and refined rubber (Hevea brasiliensis) seed oil (RSO) via the transesterification route [119]. The biodiesel's yield, physico-chemical composition, and fuel characteristics were identified. The fuel's physical, chemical, and functional characteristics were contrasted with those of commercial diesel fuel. The crude RSO's methyl ester yield was in the following order: (3)> (4)> (2)> (5)> (5)> (1), while the refined oil's production was as follows: (2)> (1)> (3)> (4)> (6)> (5). In general, sample I, made from the raw RSO and catalyzed by sodium hydroxide, had the lowest yield (15%), whereas sample II, made from the refined RSO and catalyzed by sodium metal, had the highest yield (92.1%). Comparative studies comparing the characteristics of biodiesel to those of conventional diesel fuel revealed that transesterification enhanced the oil's fuel qualities. While the predicted fuel potential increased, the viscosity and %free fatty acid values decreased. The ASTM criteria were determined to be met by other fuel characteristics.

By using a heterogeneous catalyst based on natural zeolite, Pulungan *et al.* (2021) have converted rubber seed oil into biodiesel [120]. The processes used to create active natural zeolite include calcining and activating (ZAA). In order to create a bifunctional catalyst, ZAA are metal oxides of PbO, ZnO, and $ZrO_2$ that have been wet impregnated. At 60 °C for 60 minutes, 5% (w/w) catalysts were used for the catalyst activity test in the biodiesel synthesis process. Catalyst crystallinity rose following the activation process and $ZrO_2$ loading but reduced following PbO and ZnO loading. Due to the dealumination process and the decreased impurities, the catalyst components after modification had lower Al levels. After impregnation, catalysts' specific surface area dropped but their overall pore volume increased. The impact of loaded metal oxides increases biodiesel conversion and decrease FFA concentration. The $ZrO_2$/ZAA catalysts performed best, converting FFA to methyl ester at a rate of 86.22% and yielding a conversion of 58.10%. The properties are a density of 0.880 g/cm3, a water content of 0.092%, and FFA contents of 1.081%, respectively. These results demonstrated the possibility for rubber seed oil-based biodiesel, which was catalyzed by a bifunctional catalyst, to be developed as a substitute source of future renewable fuels.

In addition to the traditional chemical techniques of producing biodiesel, lipase-catalyzed transesterification is gaining greater attention. Due to its capacity for simultaneous transesterification and esterification, ease of product separation from the enzyme and glycerol, and reduction in inhibition rate, it has attracted more attention [23]. Moreover, unlike chemical trans-esterifying agents, lipases are not sensitive to the majority of free fatty acids (FFA). *Pseudomonas aeruginosa* BUP2, a strain that produces a lot of lipases, was recently introduced by a group [121]. Numerous species, such as bacteria, fungus, and yeast, as well as mammals and plants, produce lipases, a subclass of esterase that catalyzes the breakdown of lipids into glycerol and long-chain fatty acids [122]. Additionally, lipase can participate in the processes of hydrolysis, esterification, inter-esterification, and transesterification. Microbial lipases are frequently utilized in industry due to their wide range of catalytic activities, simplicity of genetic manipulation, high yield, exponential proliferation of the generating microorganisms in low-cost media, and lack of seasonal variations [123]. The most common genera of bacteria and fungus that produce lipases include Pseudomonas, Bacillus, Serratia, and Alcaligenes, as well as Aspergillus, Penicillium, and Candida [124]. Panichikkal *et al.* (2018) present the characteristics of rubber seed oil (RSO) and discuss its possible use in the lipase-catalyzed transesterification of biodiesel (Figure 1) [125]. Newly discovered Pseudomonas aeruginosa strain BUP2 bacterium produced lipase. The combined effect of several

independent parameters, including the oil-methanol ratio, enzyme unit, reaction temperature, and reaction duration, was optimized using Response Surface Methodology (RSM) and Box-Behnken Design (BBD). At the optimum level of lipase (750 U), methanol ratio (1:10), temperature (45 °C), and time during the validation procedures, biodiesel yield of 99.52% was attained (4 h). The fuel characteristics of the biodiesel obtained under the validation condition complied with ASTM D6751 and EN 14214 criteria (Table 1). The study of Panichikkal *et al.* (2018) illustrates a significant application of a prospective fossil fuel replacement made from raw feedstocks of high economic value [125].

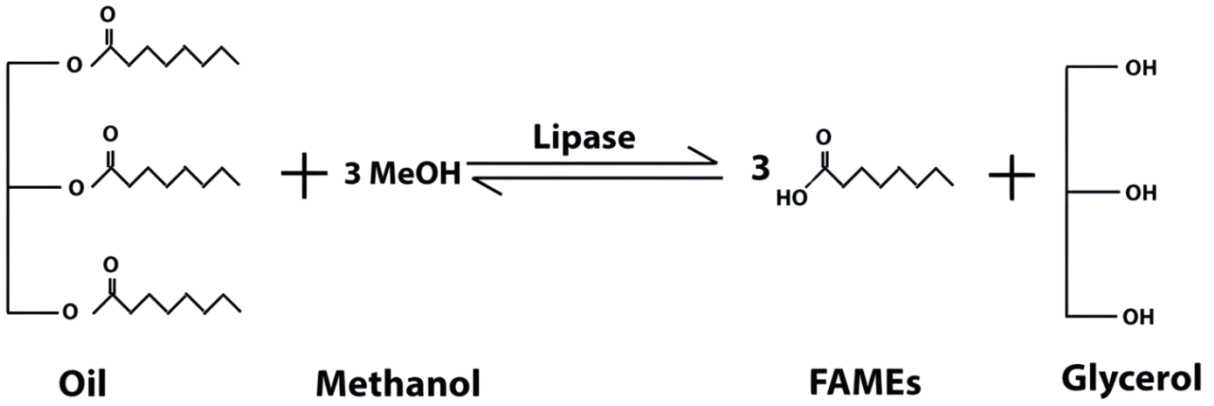



Fig. 2: Action of lipase; RSO with methanol in the presence of lipase to form fatty acid methyl esters and glycerol [125]

Table 1: Fuel properties of biodiesel [125]

| Properties | Methods | Unit | Limits | Standards | Biodiesel |
|---|---|---|---|---|---|
| Ester content | EN14103 | wt% | 96.5 min | EN14214 | 99.52 |
| Free glycerol | EN14105 | wt% | 0.02 max | EN14214 | 0.00 |
| Monoglyceride | EN 14214 | wt% | 0.8 | EN14214 | 0.30 |
| Triglyceride | EN 14214 | wt% | 0.20 | EN14214 | 0.18 |
| Total glycerol | EN14105 | wt% | 0.25 max | EN14214 | 0.20 |
| Acid value | EN14104 6751 4.82 | EN14104 6751 4.82 | | | |
| Density | EN ISO 3675 | g/m3 | 860–900 | EN14214 | 884 |

The acceptable low temperature characteristics and oxidation stability of the synthesized methyl esters are the primary issues. These issues are directly related to the chemical makeup of the feedstock used to make the methyl esters, which has a high concentration of fatty acids. Because saturated methyl esters (SME), which make up a large portion of palm oil methyl esters (POME), have poor low-temperature characteristics and tend to form crystals in cold climates, smooth fuel flow for ignition is constrained [7]. In contrast, rubber seed oil methyl esters (RSOME) have a high concentration of poly-unsaturated methyl esters that include double bonds and a low number of SME. The quantity of double bonds and their locations determine how vulnerable unsaturated methyl esters are to autoxidation. The fuel's viscosity, acid value, and peroxide value decrease due to biodiesel's poor oxidation stability, which causes engines to malfunction [126]. A prior study found that the characteristics of biodiesel developed by combining several methyl esters significantly improved [127]. In order to enhance POME's low temperature characteristics and oxidation stability, Bokhari *et al*. (2014) blended POME with RSOME at various ratios [128]. In a similar vein, all post-blend products underwent testing in accordance with worldwide biodiesel standards EN 14214 and ASTM D671 [101]. For the base transesterification reaction of POME and RSOME, kinetic parameters were computed. Rubber seed oil methyl esters (RSOMEs), which are non-edible and contain considerable amounts of unsaturated fatty acids, helped to improve low temperature characteristics. The resulting fuel's low temperature qualities were enhanced by post-blending POMEs and RSOMEs at various volumetric ratios. Induction periods (IP) of 25.52 h for POMEs were superior to RSOMEs' 3 h IP, which led to exceptional oxidation stability. RSOMEs, on the other hand, behaved well with regard to low temperature properties. With the post-blend mixture's decreased saturation of methyl esters, GC analysis showed a considerable improvement in low temperature

characteristics. The blend ratio of POMEs to RSOMEs at 20:80 was found to be the optimal blend value, where both low temperature characteristics and oxidation stability were evaluated at acceptable levels. All of the mixes met the EN and ASTM worldwide biodiesel standards (Table 2). POME and RSOME transesterification kinetics followed pseudo-first order kinetics. Both POME and RSOME had activation energies of 33.2 kJ/mole and 43.4 kJ/mole, respectively. It was discovered that the frequency factors for POME and RSOME were, respectively, 2.4 x 103 $min^{-1}$ and 1.3 x 103 $min^{-1}$.

**Table 2**: Post blended biodiesel fuel properties [128]

| Fuel properties | Units | EN 14214 Criteria | ASTM D671 Criteria | POME: RSOME (vol %) | | | |
|---|---|---|---|---|---|---|---|
| | | | | 80:20 | 60:40 | 40:60 | 20:80 |
| Esters | % mass | 96.5 | - | 97 | 96.8 | 96.6 | 96.2 |
| Acid Value | mg KOH/g | 0.5 max | 0.5 max | 0.39 | 0.40 | 0.38 | 0.39 |
| Moisture Content | % volume | 0.05 max | 0.05 max | 0.01 | 0.01 | 0.02 | 0.01 |
| Oxidation Stability | Hr | 6 | - | 14.21 | 13.48 | 10.54 | 8.9 |
| Sulphur Content | % mass | 0.01 max | 0.05 max | 0.01 | 0.02 | 0.01 | 0.01 |
| Flash Point | °C | 120 min | 130 min | 153 | 155 | 155 | 153 |
| Heating Value | kJ/g | 35 min | - | 40.1 | 39.6 | 39.9 | 39.8 |
| Free Glycerine | % mass | 0.02 max | 0.02 max | 0.006 | 0.008 | 0.006 | 0.0053 |
| Total Glycerine | % mass | 0.24 | 0.25 | 0.05 | 0.07 | 0.078 | 0.080 |

At the moment, only a tiny percentage of rubber seeds are used in the breeding process of rubber plants, and the majority of seeds are just left to rot. Rubber seed oil (RSO) millers face a waste management challenge since rubber seed shells (RSSs) produced during oil extraction come from seeds. As a potential solid base catalyst for the transesterification of esterified rubber seed oil (RSO) to biodiesel, Onoji *et al.* (2017) explored discarded rubber seed shell (RSS) [129]. The catalyst was characterized using the following techniques: TGA, XRF, XRD, SEM, and N2 adsorption/desorption analysis (BET). The experiments performed to determine how the process factors (reaction time, methanol/oil ratio, and catalyst loading) affected the production of biodiesel were designed using central composite design (CCD). The process was optimized using the Response Surface Methodology (RSM) technique, and the quadratic model that was created had a statistically significant F-value of 12.38 and p-value (0.05). The reaction period (60 min), methanol/oil ratio (0.20 vol/vol), and catalyst loading (2.2 g) are the ideal conditions as determined by RSM, with a maximum biodiesel yield of 83.11%, which was empirically verified as 83.06 0.013%. The catalyst's reusability test under ideal circumstances reveals that the biodiesel production was greater than 80% after the fourth cycle of use and that the amount of leached $Ca^{2+}$ ions in the biodiesel was 3.26 mg/kg (ppm). Both the oxidation stability of the biodiesel and its ester concentration, as evaluated by a calibrated gas chromatography, are 7.8 hours and 96.7%, respectively. The biodiesel that was described met the requirements of ASTM D 6751 and EN 14214. (Table 3). The findings indicate that modern diesel engines may run on biodiesel made from rubber seed shell oil using a waste rubber seed catalyst without any technological adjustments.

**Table 3**. Fuel Properties of Biodiesel from Rubber Seed Oil [129]

| **Properties** | **Methods** | **ASTM D 6751** | **EN 14214 standards** | **The study of Onoji *et al.* (2017) [129]** |
|---|---|---|---|---|
| Density @ 15 °C (kg/m3) | ASTM D 1298 | 870−900 | 860−900 | 876 |
| Water and sediment (vol %) | ASTM D 2709 | <0.05 | <0.05 | 0.0062 |
| Acid value (mg KOH/g) | ASTM D 664 | <0.8 | <0.5 | 0.56 |
| Iodine value (g I2/100 g) | Wijs' | | 120 Max | 85.34 |
| Saponification value (mg KOH/g) | | | | 182.53 |
| Kinematic viscosity @ 40 °C (mm2/s) | ASTM D 445 | 1.9−6.0 | 3.5−5.0 | 4.32 |
| Flash point (°C) | ASTM D 93 | 93 minimum | 120 minimum | 158 |
| Fire point (°C) | | | | 172 |
| Cloud point (°C) | ASTM D 2500 | −3 to 12 | | 4.8 |
| Pour point (°C) | ASTM D 97 | −15 to 10 | 0 | −8 |
| Cold filter plugging point (°C) | ASTM D 6371 | | | -0.62 |
| Calorific value (MJ/kg) | ASTM D 240 | | | 40.67 |
| Oxidation stability: @ 110 °C (h) | Rancimat | ≥3 | ≥6 | 7.8 |
| @ 140 °C (min) | PetroOXY | ≥17 | | 21.55 |
| Cetane number | ASTM D 613 47 | 47 minimum | 51 minimum | 57 |
| Metals: Group II (Ca-ppm) | EN 14538 | | 5 | 3.26 |
| Ester content (%) | EN 14103 | | ≥96.5 | 96.7 |

For the synthesis of biodiesel, Ahmad *et al.* ((2014) used a non-edible rubber seed oil (RSO) with a high free fatty acid (FFA) concentration of 45% [101]. Two steps are involved in the procedure. The base transesterification follows the acid esterification in order to lower the FFA value. Acid esterification and base transesterification are two-stage processes that were parametrically optimized using the response surface methodology (RSM). Gas chromatography was used to evaluate the yield of biodiesel. Another method used to validate the transformation of fatty acids into methyl esters was the FTIR (Fourier Transform Infra-Red) spectrum. As stated in Table 4, the ASTM D6751 and EN 14214 standards were used to examine the RSO FAME fuel's qualities. No additional modifications are required because the viscosity of the synthesized RSO biodiesel is within the requirement. Since RSO methyl ester has a greater flash point than diesel, it can be kept with less risk. Because there are more unsaturated fatty acids present than saturated fatty acids, RSO FAME has notably good low temperature characteristics. One of the most crucial fuel characteristics that affected the effectiveness of storage and use is oxidation. The obtained oxidation stability and the Cold Filter Plugging Point (CFPP) display results that are comparable to those of other research that have been published and that adhere to recognized criteria. From a storage perspective, the biodiesel's flash point (FP) is crucial since a greater FP reduces the likelihood of flaming. The primary factor to consider when choosing biodiesel as an alternative fuel to pure vegetable oil is its kinematic viscosity. The type of fatty acids and their degree of saturation and unsaturation have a direct impact on viscosity. The viscosity will be reduced if the amount of unsaturated fatty acids is higher. The rubber seed oil biodiesel in this investigation met the requirements of ASTM D6751 and EN14214 with a kinematic viscosity of 3.89 $mm^2/s$. According to Melvin *et al.* (2011), the kinematic viscosity is also seen to be lower than that of rubber seed oil-based biodiesel [130]. Three general parameters—cloud point, pour point, and cold filter plugging point—are typically used to determine the cold flow characteristics of biodiesel [131]. The degree of saturation and unsaturation, the length of the carbon chain, the orientation of the double bonds, and the makeup of the fatty acid are all factors that affect the cold flow qualities. Fatty acids' melting point rose as their carbon atom count grew [132]. For illustration, the melting point of C12:0 is 5 °C, while that of C18 is 39 °C. A reverse scenario was seen, where the melting point drops as the degree of unsaturation increases. For instance, the melting points of and C18:3, C18:2, C18:1 and C18:0, are -52 °C, -35 °C, -20 °C and 39 °C, respectively [131]. RSO FAME displays a cloud point of 3.2°C, a pour point of -2°C and a CFPP of 0°C [130]. Due to a higher content of unsaturated fatty acids, the results of the cold flow properties are improved. Using the Rancimate method outlined in EN 14112, the oxidation stability of RSO FAME was evaluated. In terms of fuel storage and performance, oxidation stability is the most crucial component. The poor oxidation stability of biodiesel is caused by the rise in viscosity, gumming, and deposition of undesirable particles during storage [133]. Although RSO FAME oxidation stability fulfills both the ASTM D6751 and EN

14214 standard levels. Ahmad *et al.* (2014) found that the oxidation stability value for RSO FAME, 8.54 h, was greater than that found in previous investigations on rubber seed oil biodiesel [101].

**Table 4:** Fuel Properties of RSO Biodiesel [101]

| Property | Units | Methods | RSOFAME | ASTM D6751 | EN14214 |
|---|---|---|---|---|---|
| Density | 25 °C kg/m$^3$ | ASTMD 5002 | 885 | N/A | 860–900 |
| Viscosity | mm2/s, 40 °C | ASTM D 445 | 3.89 | 1.9–6.0 | 3.5–5 |
| Cetane Number | - | ASTM D 613 | 54 | 47 min | 51 min |
| Oxidative stability h | h | EN 14112 | 8.54 | 3 min | 6 min |
| Cloud point | °C | ASTM D 97 | 3.2 | – | – |
| Pour point | °C | ASTM D 2500 | -2 | - | - |
| Cold Filter Plugging Point | °C | ASTM D 6371 | 0 | - | - |
| Flash Point | °C | ASTM D 93 | 152 | 93min | 120min |
| Higher Heating Value | MJ/kg | ASTM D 4868 | 39.70 | - | - |
| Free Glycerin | % | ASTM D 6584 | 0.02 | 0.02 max | 0.02 max |
| Total Glycerin | % | ASTM D 6584 | 0.35 | 0.24 max | 0.25 max |
| Moisture Content | % | ASTM D 2709 | 0.042 | 0.05 max | 0.05 max |
| Acid Value | mg KOH/g | Cd 3d-63 | 0.42 | 0.50 max | 0.50 max |
| Ester Content | % | EN 14103 | 96.8 | N/A | 96.6 |

Through the use of methanol and a heterogeneous catalyst, Trirahayu *et al.* (2022) seek to mimic and simulate the transesterification reaction used to produce biodiesel from RSO [97]. Using ASPEN Hysys v11, the simulation was run. It was decided to use acid-based catalyzed esterification to prevent soap production, which might considerably reduce biodiesel yield. The findings indicated that 1146 L/h of biodiesel could be produced from an RSO with an inlet rate of 1100 L/h and a methanol to oil molar ratio of 1:6. Methanol recovery was done, and it was possible to regenerate about 95% of the extra methanol. According to simulation findings, the manufactured biodiesel has qualities that make it compatible with contemporary diesel engines. The Trirahayu *et al.* (2022) study's biodiesel product qualities were compared to those from the aforementioned studies [97]. Unfortunately, the researchers were only able to compare a small number of biodiesel properties due to limited access to analytical tools (Table 4). Generally speaking, the qualities of the biodiesel created by this work are comparable to other papers on RSO's laboratory-scale biodiesel synthesis (Table 4). With the exception of viscosity, the product's attributes are found to fall within the scope of the biodiesel properties mentioned in ASTM D 6751 and EN 14214. (Table 4). The potential of this technology and its outstanding investment criterion are also shown by economic studies.

**Table 4.** Product properties obtained from this study in comparison with other products from the literature [97]

| Properties | ASTM D 6751 Standards | EN 14214 Standards | Onoji *et al.* (2017) [129] | Ahmad *et al.* (2014) [101] | The Study of Trirahayu *et al.* (2022) [97] |
|---|---|---|---|---|---|
| Water & sediment, | max <0.05 | <0.05 | 0.0062 | 0.042 | 0.01 |
| Viscosity (cSt) @ 40 °C | 1.9–6.0 | 3.5–5.0 | 4.32 | 3.89 | 1.811 |
| Density @15 °C (kg/m$^3$) | 870–900 | 860–900 | 876 | 885 | 880.6 |
| Ester content | | >96.5 | 96.7 | 96.8 | 99.93 |

**Performance of Rubber Seed Oil Biodiesel on Diesel Engine**

It is crucial to test the performance of biodiesel in a diesel engine to make sure that the emissions comply with the set standards and that it can be used as fuel. Diverse researchers have done studies to examine the efficiency of biodiesel and its blends in an engine and conduct emission analysis using biodiesel made from various feedstocks [134-135]. The development of biodiesel using vegetable oils as feedstocks and its use in compression ignition engines was first studied in 1893 by a German scientist by the name of Rudolph Diesel [41]. At a world exposition in Paris in 1900, a French company stated that biodiesel made from peanut oil could be used in diesel engines [136].

In 1941, Henryford, a car manufacturer, unveiled a soyabean vehicle [137]. Brazil launched the first commercial use of rapeseed oil-based biodiesel in 1977. The 1992 Energy Policy Act made using alternative fuels a requirement for Car Maker Companies. In the United States, the first commercial biodiesel operation began in 1996 [138]. India launched its first biofuel-powered flight on August 27, 2018, between Dehradun and Delhi. Promising results were also reported by recent studies on the use of biodiesel in diesel engines. Various blends of biodiesel B10, B20, and B30 with regular diesel were tested in engines and managed to convert *Pongamia* oil to biodiesel at a rate of 95.7% utilizing modified KI/CaO as a catalyst [135-136]. Compared to B10 and B20 gasoline, it has been found that B30 fuel has poorer brake thermal efficiency (BTE) and a greater brake specific fuel consumption (BSFC). Comparing B30 blend to regular diesel, NOx emissions were found to be greater, but emissions of carbon monoxide (CO), total hydrocarbons (THC), and smoke were all lower [139]. Blends of B10, B20, B50, and B100 were tested with biodiesel made from used cooking oil using KBr/CaO as a catalyst [140]. In contrast, low BTE was noted for blends, and the highest BTE was noted at 75% engine load. It was also noted that the BSFC increased with an increase in blend ratio and decreased with an increase in load. Additionally, when compared to standard diesel, low CO and THC emissions and significant NOx emissions were seen [140]. It has been tested to see how well engines run when biodiesel is produced from used frying oil utilizing KF impregnated on bivalve clam shells. According to the findings of this investigation, as compared to conventional diesel, a minimum BSFC and maximum BTE were seen at loads of B20, B40, B60, and B80 [141]. A decrease in THC, CO, and smoke and an increase in NOx were seen with an increase in biodiesel blends. Engine performance and emissions under various loads of B10, B20, B50, B75, and B100 were tested while utilizing rubber seed oil (RSO) biodiesel, with B10 exhibiting an improvement in BTE and a decrease in BSFC. Increases in biodiesel blends were found to result in an increase in NOx emissions while decreasing THC and CO emissions [140]. At a constant engine speed of 1500 rpm, three different blends of biodiesel made from used cooking oil were evaluated for their effects on diesel engines. When compared to conventional diesel, the prepared biodiesel blends had low BTE, CO, and THC levels, but an increase in NOx emissions was also seen as the biodiesel blends were increased. The literature cited above focused on the use of biodiesel made from various edible and non-edible oils in a diesel engine. Due to rivalry with the food chain, high demand, and their pricey nature, the use of various edible oils for the production of biodiesel is not supported in the majority of developing nations, particularly Nigeria. Nigeria is home to numerous non-edible oil-bearing seed trees, including *pongamia*, rubber seed, neem, jatropha, and others. The oil derived from these non-edible seeds was tested in numerous recent research investigations with various mixes in diesel engines to verify the emission and performance characteristics as described in the literature. Rubber seed oil, which is made from inedible seeds and mostly found in different parts of Nigeria, is still one of these oils that is most prevalent there.

The performance and emission properties of rubber seed oil biodiesel, an oxygenated fuel, are recognized to be environmentally beneficial, with significant decreases in smoke opacity, exhaust gas temperature, and oxides of carbon, nitrogen, and sulfur [142]. According to an earlier report, the absence of sulfur and aromatic components in rubber seed oil biodiesel precludes the development of SOx and PAHs, respectively [143]. The observed performance indicators for rubber seed oil biodiesel's brake power,

torque, brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC) are fairly positive for the fuel's adoption as a substitute in the near future. In comparison to rubber trees from other places, the NIG800 series typically generates 3000–3500 kg of dry natural rubber per hectare per year and approximately 1200 seeds per tree per year [144]. As of the year 2020, there was no research on the Nigerian bioengineered rubber tree (Hevea brasiliensis, NIG800 series) that was used to make biodiesel from the rubber seed oil with regard to its emission characteristics or engine performance. The performance and emission characteristics of a TD202 diesel test engine running on rubber seed oil biodiesel, diesel, and their blends were therefore evaluated by Onoji *et al.* (2020) [144]. The biodiesel's lack of sulfur, low level of aromatics, and high level of oxygen all helped to lower emissions of carbon monoxide, unburned hydrocarbons, and soot. The modest increase in carbon dioxide emissions from biodiesel was partially offset by plants' ability to absorb carbon dioxide. The following are the main conclusions of this study:

- In comparison to diesel, the BSFC of biodiesel and blends was greater (Figure 2). This is brought on by the reduced heating value of biodiesel (8–12% drop). For the same engine output as diesel fuel, higher BSFC requires using more biodiesel and mixes.
- Due to biodiesel's lower energy content compared to diesel, engine BP (brake power), BTE (brake thermal efficiency), and torque (Figures 3, 4) are lower for biodiesel and all blends.
- As the amount of biodiesel in the blends grew, the CO2 and NOx emissions significantly increased with speed, virtually linearly. This is mostly due to the high combustion chamber temperature and the biodiesel's high oxygen concentration, which permits almost complete burning.
- When compared to diesel, other pollutants like CO, THCs, and smoke were dramatically reduced by biodiesel and its mixes. The absence of aromatic molecules, the biodiesel's lower carbon content, and its higher $O_2$ content are proposed explanations for this behavior.
- To learn more about the biodiesel combustion characteristics of the TD202 diesel engine, more investigation is required (ignition point, premixed and diffusion combustions, heat release rate, crank angle analysis, etc.).

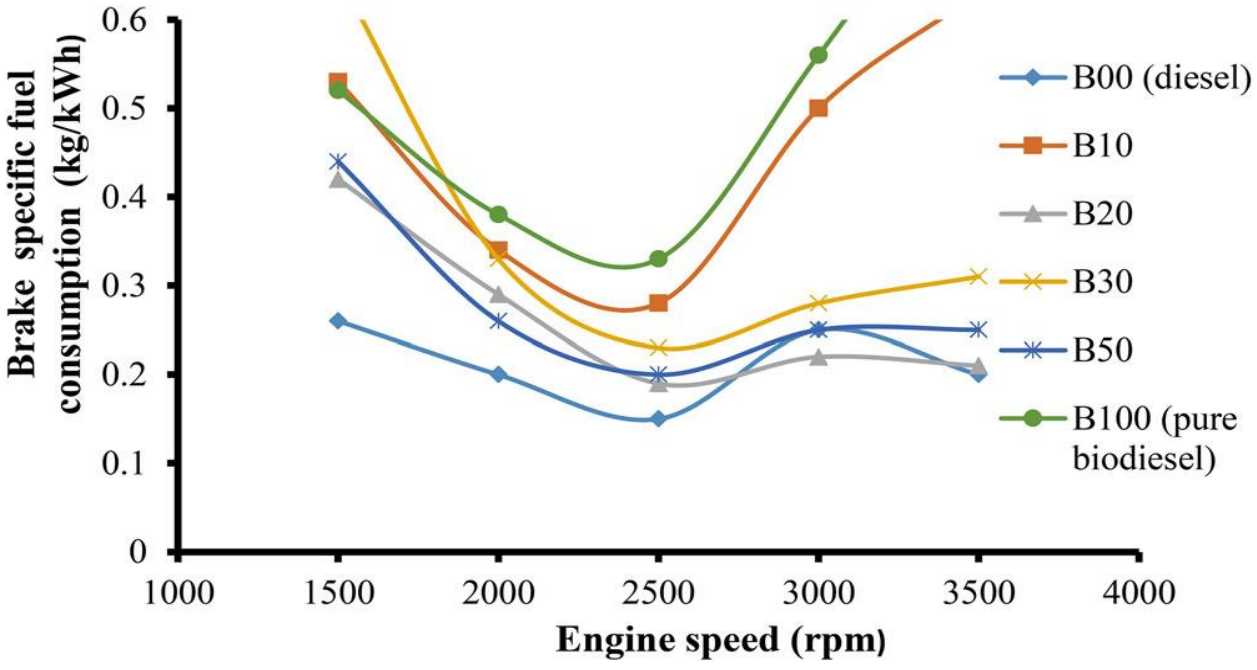



**Figure 2.** Variation of brake specific fuel consumption with speed for diesel and biodiesel blends [144]

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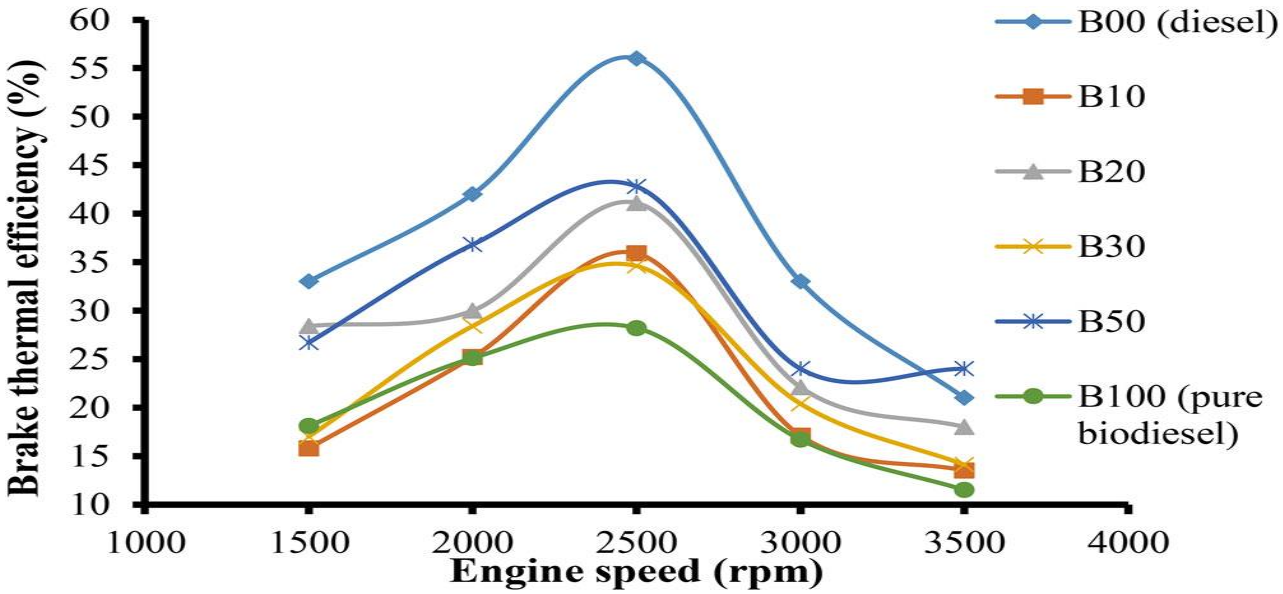


**Figure 3.** Variation of brake thermal efficiency with speed for diesel and biodiesel blends [144]

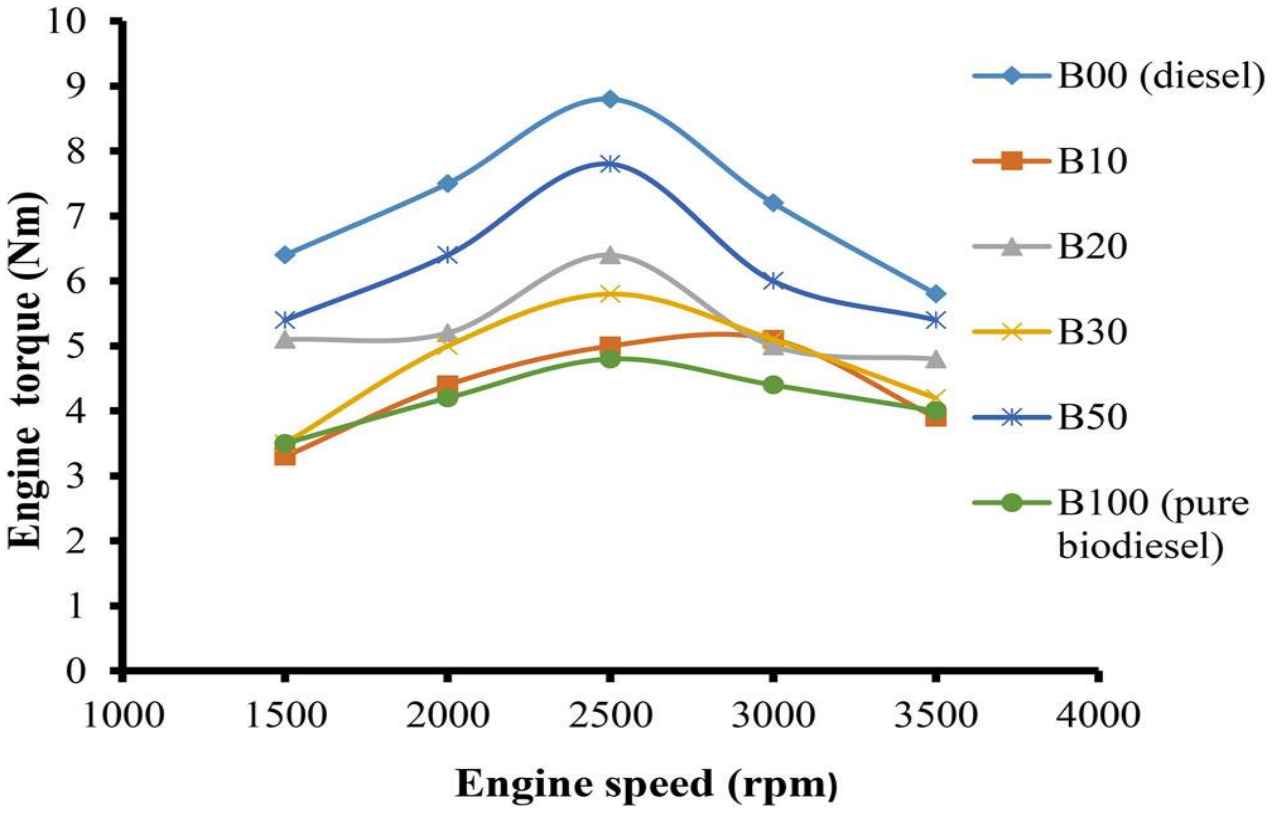


**Figure 4**. Variation of engine torque with speed for diesel and biodiesel blends [144]

In a single cylinder, four-stroke diesel engine running at a constant speed of 1500 rpm, Patil & Patil (2017) assessed the combustion, performance, and emission characteristics of refined biodiesel (biofuel) such rubber seed oil methyl ester with the partial addition of n-butanol (butanol) [145]. Figure 5 shows a schematic design of a diesel engine configuration. The characteristics of neat rubber seed oil methyl ester (100%) and neat diesel (100%) at various load conditions on engines (such as 0%, 25%, 50%, 75%, and 100% for the compression ratio) were compared with the characteristics of butanol-rubber seed oil

methyl ester blends with varying volume percentages of butanol, such as 5%, 10%, 15%, and 20%. At full load, conditions that were economical and environmentally favorable were seen. When butanol content in rubber seed oil methyl ester (ROME) grows from 5% to 20%, performance metrics like brake-specific fuel consumption rise by 17% and BTE fall by 14% at full load (Figure 6). At full load, it is noted that neat diesel uses less brake-specific fuel (0.25 kg/kWh for neat diesel, 0.30 kg/kW/h for neat ROME, and approximately 0.325 kg/kW/h for butanol-ROME blends), while the BTE of neat biofuel ROME (35%) was more promising than that of the other tested five fuels (32% for neat diesel and roughly 30% for butanol-ROME blends). Therefore, butanol-ROME blends are less effective than neat diesel or neat ROME from the perspective of performance characteristics. Less than 0.1% and 35 ppm, respectively, of carbon monoxide and hydrocarbon (HC) emissions were recorded in all tested fuels at full load conditions. A significant point is that in ROME, as butanol percentage increases from 5% to 20%, NOx emissions at full load reduce by 10%. Butanol-ROME blends emit more NOx than neat ROME, although having NOx emissions that are less than neat diesel (about 280 ppm) (140 ppm). In light of emission characteristics, butanol-ROME blends are therefore more effective than neat diesel but less effective than neat ROME. It has been determined that the neat ROME and butanol-ROME blends emit NOx, CO, and HC levels below the safe limit for environmental pollution set forth by EURO-6 standards. The four butanol-ROME blends tested for power generation and for diesel vehicles are less promising than neat diesel in terms of performance and emission characteristics. Instead, neat ROME appears to be more promising. It is possible to research the combined effects of VCR and exhaust gas recirculation in existing diesel, though.

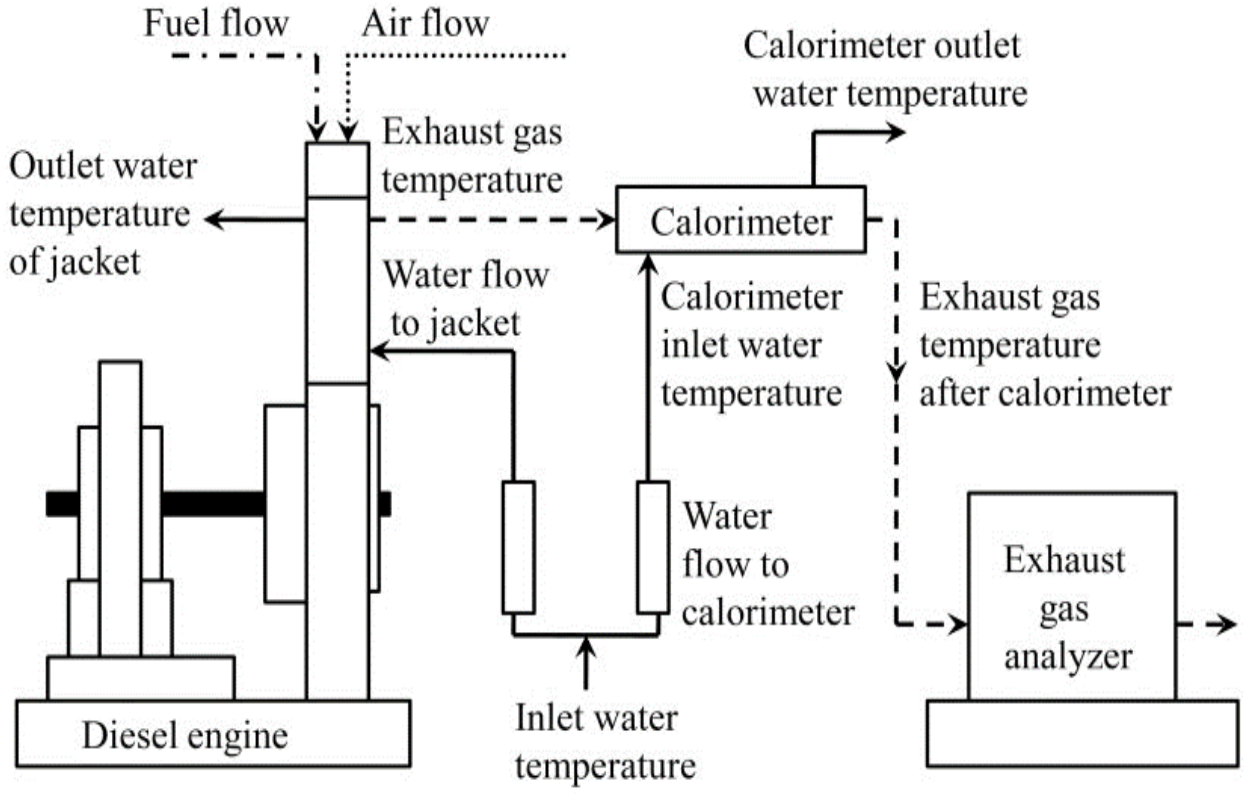


Figure 5. Schematic diagram of diesel engine setup [145]

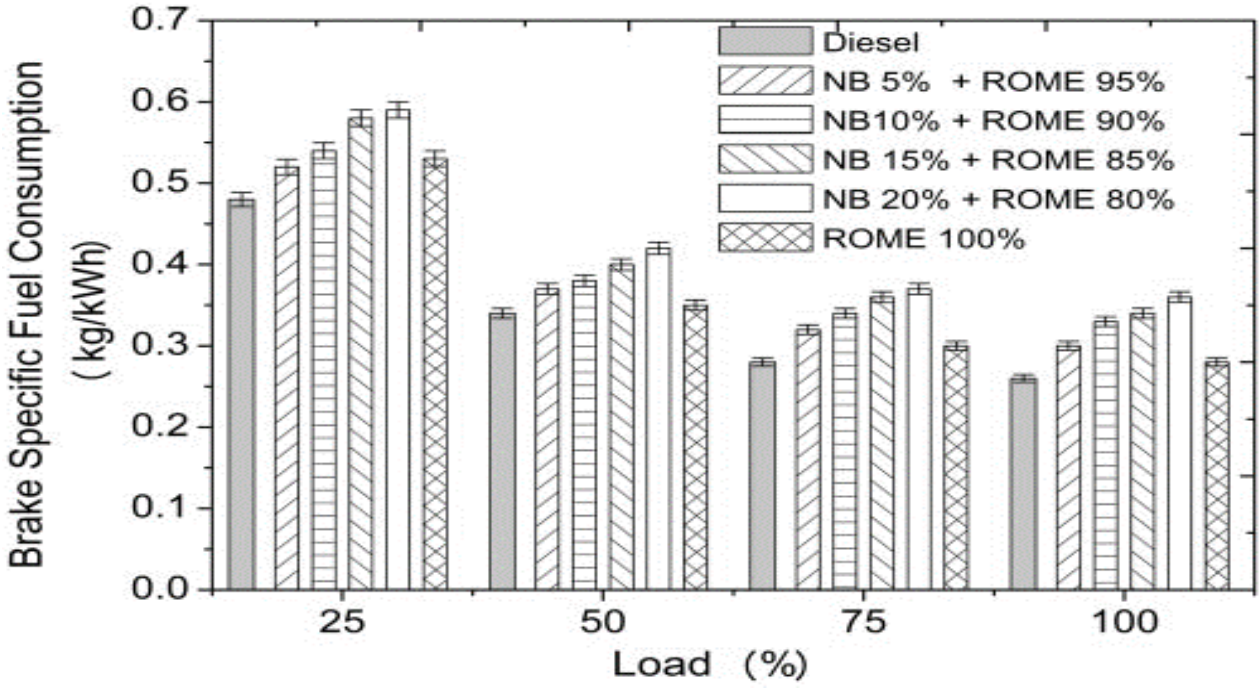


**Figure 6**. Variation of brake specific fuel consumption with load [145] (Patil & Patil, 2017).

A number of studies have looked into the use of rubber seed oil-based biodiesel produced utilizing homogeneous catalysts in diesel engines. Since homogeneous catalysts like KOH, NaOH, etc. cannot be recycled and require additional water during the purification process, their use in the synthesis of biodiesel is not promising. To solve these problems, heterogeneous base catalysts can be used in place of homogeneous catalysts. Today, it is more encouraged to use heterogeneous catalysts made from various waste materials, such as eggshells, calm shells, cockles' shells, etc., in the synthesis of biodiesel since they produce a final product that is affordable. Sai Bharadwaj *et al. (*2021) evaluated the effectiveness and emission assessment of biodiesel produced at optimum processing conditions of 4 (wt.%) of catalyst concentration, 12:1 methanol: oil molar ratio, and 3 h of reaction time is examined in a diesel engine for 3 distinct blends, namely B10, B20, and B30, respectively [146]. For all blends, it was found that when brake mean effective pressure increased, brake thermal efficiency gradually increased and brake specific fuel consumption marginally decreased. The minimum brake specific fuel consumption for a B10 blend is 0.3895 (kg/kWh), which is quite close to the number achieved from petroleum diesel (0.38 (kg/kWh)). When compared to standard diesel, which had a value of 75.8 (%), the highest brake thermal efficiency was found to be 73.26 (%) for B10 blend. Increases in brake mean effective pressure of each blend were also accompanied by a progressive drop in carbon monoxide (0.0275% for B30 blend), hydrocarbons (36 ppm for B10 mix), nitrogen oxide (275 ppm for B30 blend), and carbon dioxide (1.9% for B30 blend). The observed results support the notion that synthetic biodiesel, made from rubber seed oil, is a workable replacement for regular diesel.

In a few trials, biodiesel and diesel blends were utilized instead of regular fuel [147]. However, as of 2016, no data on the rubber seed methyl ester stability when utilizing antioxidants was provided. Furthermore, the majority of the publications employed antioxidant concentrations of up to 1000 ppm, although a small number of them dealt with doses as high as 2000 ppm. Only three papers [148-149] have reported on the combustion characteristics of a diesel engine using biodiesel treated antioxidants as of the time this paper was published in 2017, whereas the reported literature at that time focused on engine performance and emissions.

Rubber seed oil requires antioxidant treatment because of its extremely low oxidation stability and large amount of unsaturated fatty acids (78.73%), which makes it vulnerable to oxidative destruction during storage. Thus, employing a two-step (acid esterification and transesterification) procedure, Adam *et al.* (2017) synthesized rubber seed methyl ester in a hydrodynamic cavitation reactor [149]. They evaluated the fuel qualities of rubber seed biodiesel to EN 14214 and ASTM standards and studied the effects of antioxidants such as N, N′-diphenyl-1,4-phenylenediamine (DPPD), 2-tert-butylbenzene-1,4-diol (TBHQ), N-phenyl-1,4-phenylenediamine (NPPD), and 2-tert-butyl-4-methoxyphenol (BHA). Four antioxidants' effects on a multicylinder diesel engine's performance, combustion, and emissions were also

examined, and the outcomes were contrasted with diesel and standard biodiesel. antioxidants were added to 20% RB at 1000 and 2000 ppm doses (RB20). The findings demonstrated that, without significantly affecting physical properties, TBHQ had the greatest capacity to promote the stability of RB20, followed by BHA, DPPD, and NPPD, respectively. The tests were carried out under full load conditions in a 55-kW multicylinder diesel engine. According to the findings, RB20 produced greater maximum in-cylinder pressure of 6.7% and higher brake specific fuel consumption (BSFC) of 3.68% as compared to plain diesel (Figure 7). As comparison to RB20, the addition of antioxidants decreased the heat release rate (HRR) (Figure 8), NO (Figure 9), and maximum in cylinder pressure (Figure 10) on average by 0.854.12%, 5.7814.74%, and 1.773.97%, respectively. The commencement of combustion was identical for all antioxidant fuels (12 °CA BTDC), although diesel and RB20 had values of −10 and −13 °CA BTDC, respectively. Nonetheless, compared to RB20, emissions of carbon monoxide (CO) and hydrocarbons (HC) increased by 10.17–15.25% and 13.35–19.68%, respectively. Antioxidant-treated RB20 blends can be used in diesel engines without requiring any additional modifications.

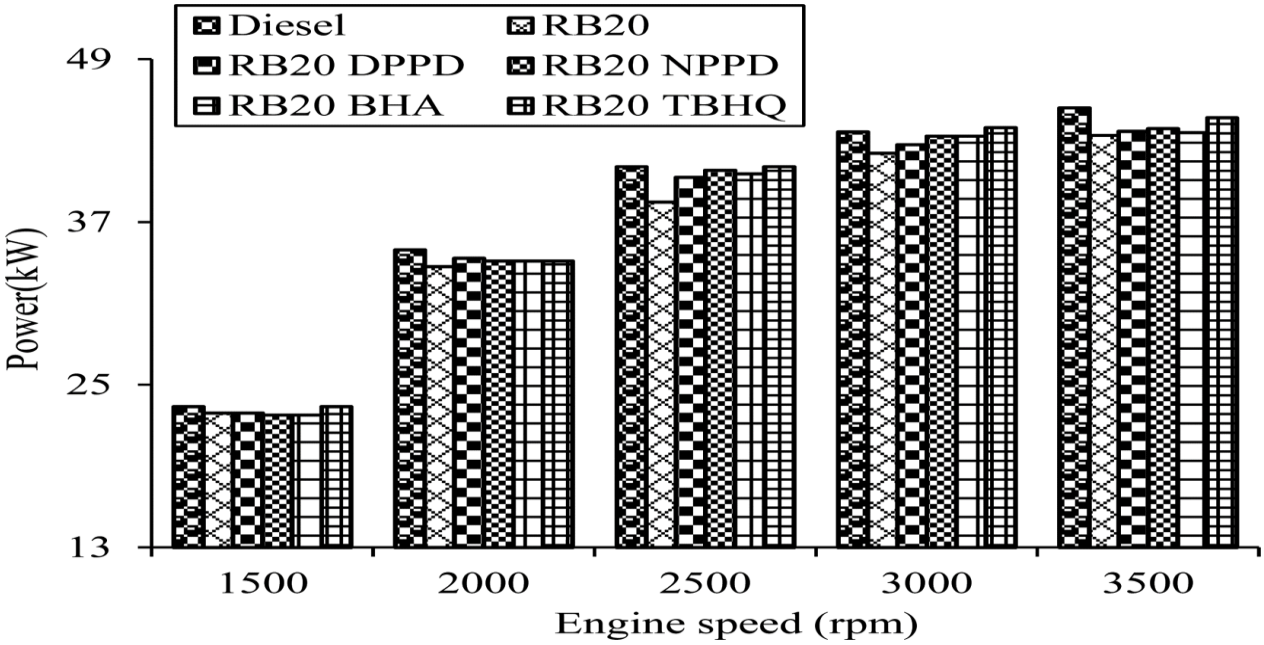


**Figure 7**. Variation of the BP with respect to engine speed [149]

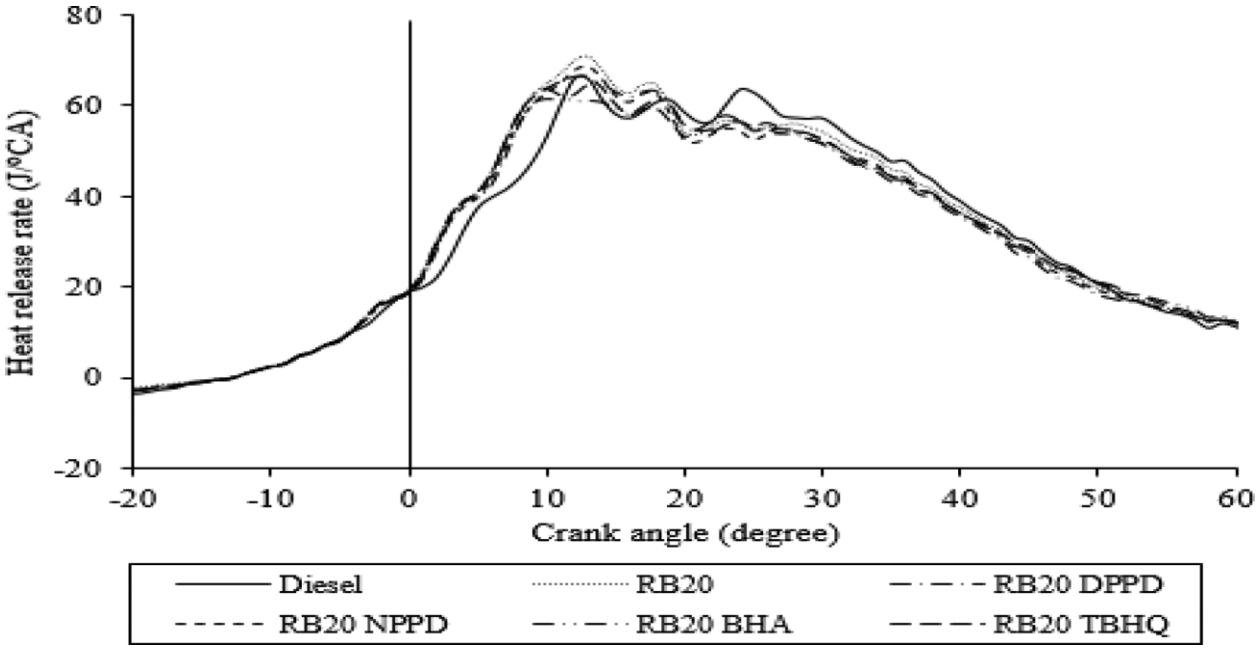


**Figure 8.** Variation of HRR at 2000 rpm at full load [149]

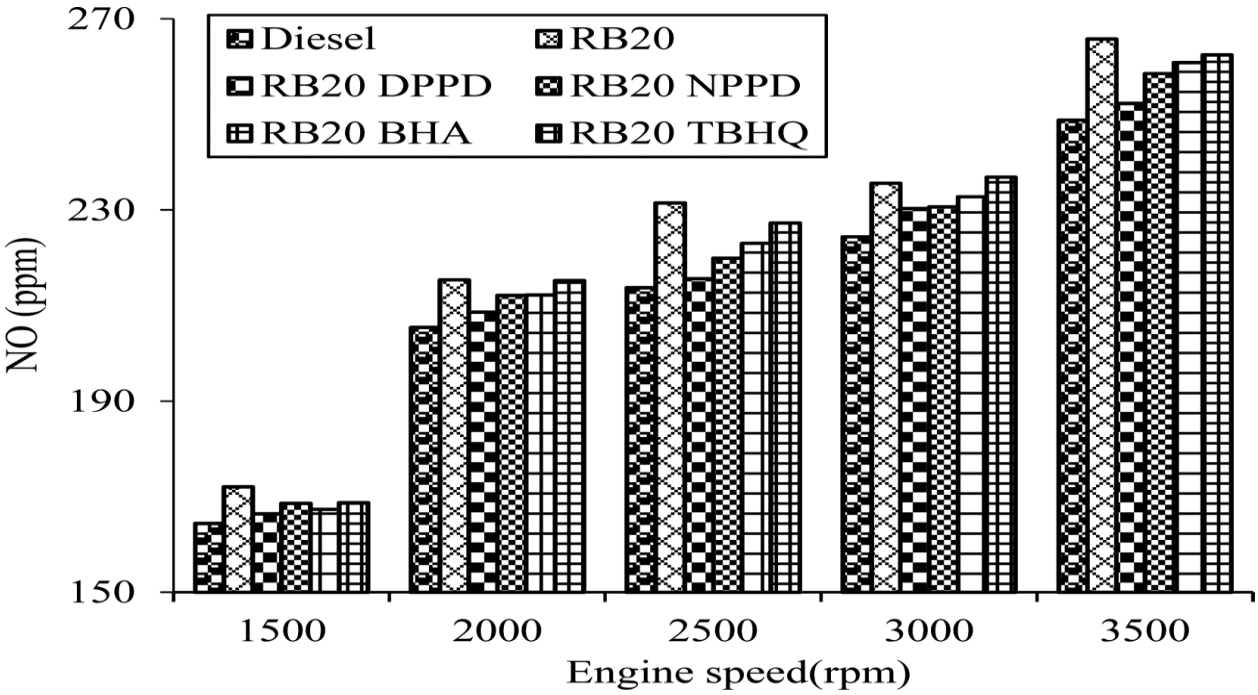


**Figure 9.** Variation of NO emission with respect to engine speed [149]

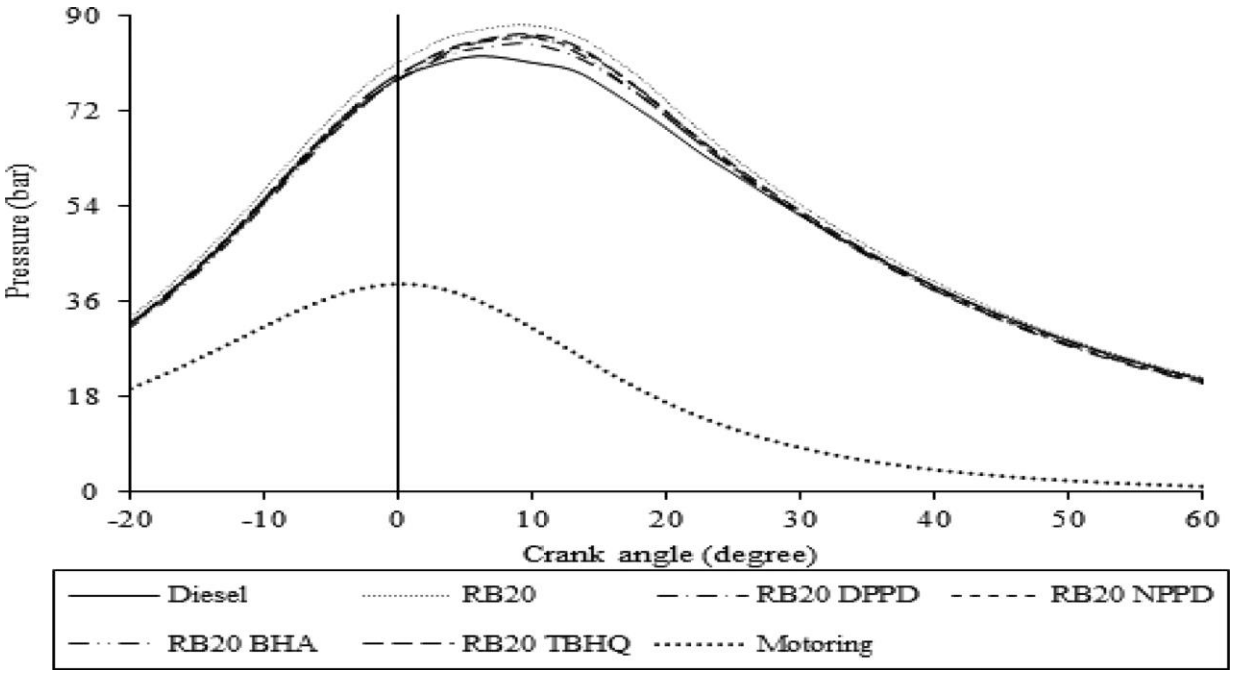


**Figure 10**. Variation of cylinder pressure at 2000 rpm at full load [149].

In a related work, Ramadhas *et al.* (2004) converted common unrefined oil rubber seed oil into biodiesel, which they then used as the fuel for diesel engines [150]. High FFA oils, such as rubber seed oil, could not be converted into biodiesel by the alkaline-catalyzed esterification process. Here, successful attempts are undertaken to produce biodiesel from raw rubber seed oil. The crude high FFA rubber seed oil is transformed into a more acceptable form of fuel for diesel engines by the two-step esterification process. Methyl esters of rubber seed oil are found to have density and viscosity that are extremely similar to diesel. It is discovered that biodiesel has a little lower calorific value than diesel. Compared to diesel, biodiesel has a greater flash point. Performance can be improved by using biodiesel blends with lower ester concentrations. The key characteristics of biodiesel made from rubber seed oil are very similar to those of diesel. Therefore, rubber seed oil's methyl esters may someday be used as a fuel or performance-enhancing additive in compression ignition engines. In compression ignition engines, different biodiesel-diesel blends are used as fuel, and their performance and emission characteristics are examined. Lower biodiesel mix proportions were discovered to increase thermal efficiency. At rated load settings, the B10 biodiesel mix significantly increases the diesel engine's brake thermal efficiency by around 3%. Additionally, employing B10 results in lower emissions and brake-specific fuel usage. Increased biodiesel blend content results in a greater decrease in smoke density in exhaust gas. As the amount of biodiesel in the blend increased, so did the temperature of the exhaust gases. Because the creation of NOx emissions is a phenomenon that is extremely temperature dependent, a rise in biodiesel mixes is likely to result in an increase in NOx emissions. The current experimental findings demonstrate that rubber seed oil methyl esters can operate satisfactorily in current diesel engines without requiring any modifications. Utilizing biodiesel as a partial diesel replacement can increase agricultural productivity, lower fuel supply uncertainty, and increase farmer independence. Additionally, this greatly aids in reducing air pollution.

The engine performance and emission characteristics of an IDI diesel engine running on biodiesel made from a blend of crude rubber seed oil were examined by Adam (2014) in a different investigation [151]. Cost reduction and property improvement are the driving forces behind the 50:50 blend. The prepared RSO biodiesel and blends of B5, B10, and B20 biodiesel to diesel were tested for their thermophysical characteristics. A 4-cylinder, naturally aspirated, indirect injection (IDI) diesel engine's torque, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE) as well as its emissions of CO, NOx, and exhaust gas temperature were assessed. The outcomes showed that for tidy diesel, B5, B10, and B20, the torque obtained at rated engine speed of 2500 rpm was 87, 86, 85.3, and 85 Nm, respectively. When compared to plain diesel, torque in all blends is between 0 and 5% less. BTE for B5, B10, and B20 were respectively 27.58, 28.52, and 26.45%, whereas neat diesel was 26.99%. When the blend ratio was lower, it was discovered that the BSFC was also lower and that it rose proportionately. As the blend ratio rises, the CO

emission decreased, but the temperature of the exhaust gas and the NOx level increased.

The goal to improve the qualities and lower the price of biofuels is what drives the blending of feedstocks. In this work, Khalil *et al.* (2016) use equal blend percentages of rubber seed and palm oil to make biodiesel [152]. Response surface methodology (RSM) was used to analyze the impacts of various factors on transesterification and estimate the maximum yield. Methyl ester was created under ideal circumstances, and its thermophysical characteristics were investigated. An unaltered indirect injection diesel engine's (IDI) performance and emissions under partial and full load were studied. According to the findings, diesel fuel had a reduced torque and brake mean effective pressure (BMEP) by 1.1 and 1%, respectively. Power and brake thermal efficiency (BTE) were both 1.1 and 1.3% lower than with diesel fuel, while full load brake-specific fuel consumption (BSFC) was 1.4% higher. Additionally, CO was decreased by 2%, while $NO_x$, $CO_2$, and exhaust temperature all saw average increases of 1.1%, 1.2%, and 1.1%, respectively.

**Conclusion**

This review discusses the current state of rubber seed oil (RSO) biodiesel as a fuel. RSO Biodiesel is essentially a fuel that may be made from rubber seed plants; as such, it can be categorized as a renewable energy source. Different techniques are used to extract the oil from these rubber seeds, and then it passes through a chemical process called transesterification. Similar to how traditional petrodiesel improves qualities like viscosity, flash point, calorific value, and cetane number, the transesterification process that turns RSO into Biodiesel (Fatty Acid Methyl Ester) benefits RSO. Internal combustion engines (ICEs) may run on RSO biodiesel without any changes. A number of scientists have conducted tests analyzing the performance of engines utilizing biodiesel made from rubber seed oil and blends of biodiesel and petroleum diesel. They discovered that the engine's performance metrics are comparable to those of traditional engines that run on petroleum. This demonstrates that in the event that conventional fossil fuels become rare in the future, biodiesel can meet the demand for fuel. Additionally, engine emissions can adhere to the varied environmental standards established by various nations. There is adequate room in this area for research to look into new and unique seeds that can be used to make biodiesel.

**Conflict of Interest**

The authors declared that there is no conflict of interest.

**Author's Declaration**

The authors affirm that the work presented is original and will accept all liability for any claims about the content.

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