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Evaluation of Crude Palm Oil-Based Biodiesel Production Using Citronella Oil as an Oxygenated Bio-Additive and Bentonite-Assisted Pretreatment

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ABSTRACT

Crude palm oil (CPO) frequently needs to be refined to fulfill quality standards, even though it is a renewable feedstock for the generation of biodiesel. This study looked into using bentonite and citronella oil together to enhance the physicochemical properties of biodiesel made from CPO. 0.90 g of bentonite and 10 mL of citronella oil produced the greatest results, with a kinematic viscosity of 3.2 cSt, a cetane number (CN) of 64.6, a free fatty acid (FFA) content of 0.24%, and a flash point of 112 ℃. While gas chromatography–mass spectrometry (GC–MS) indicated that methyl palmitate and methyl oleate were the primary constituents of Fatty Acid Methyl Esters (FAME), Fourier-transform infrared spectroscopy (FTIR) verified the existence of ester functional groups. The response surface methodology (RSM), analysis of variance (ANOVA), and Pareto diagrams were employed to assess the influence of process factors on biodiesel quality to achieve optimal conditions following treatment in the biodiesel production process. The concentration of citronella oil had a substantial impact when compared to the usage of bentonite, and there was a clear interaction between the two elements, according to data processing utilizing these techniques.

1. INTRODUCTION

Fossil diesel use and related greenhouse gas emissions have been steadily increasing due to the fast development of the transportation and industrial sectors. Air pollution, acid rain, and climate change are caused by the emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_X), sulfur dioxide (SO_2), and particulate matter from conventional diesel combustion [1]. Intense research on renewable and cleaner-burning alternative fuels has also been spurred by the depletion of fossil fuel stocks [2, 3].

Vegetable oils, animal fats, and waste lipids can all be used to make biodiesel, which is mostly made of Fatty Acid Methyl Esters (FAME). Biodiesel has a variety of advantages over fossil diesel, including renewability, an intrinsic oxygen content, a higher cetane number (CN), better lubricity, and generally reduced CO, HC, and particulate matter emissions. Because photosynthetic uptake can partially offset the mostly biogenic CO_2 emitted during combustion, net greenhouse gas emissions can be decreased [4].

Particularly in Indonesia, which is acknowledged as one of the world's top producers of palm oil, crude palm oil (CPO) is a valuable and plentiful feedstock for the generation of biodiesel. Because of its widespread availability, well-established agro-industrial supply chain, and compliance with national renewable energy laws, CPO is highly recommended for use as a feedstock for biodiesel. Fuel blends based on palm oil, such as the B40 and B50 initiatives, which seek to lessen reliance on imported fossil fuels and improve domestic energy security, have dominated Indonesia's recent use of biodiesel. By boosting the added value of the palm oil business, assisting rural agroindustry, and encouraging the use of locally available renewable resources, the growth of CPO-based biodiesel also boosts the economy [5].

Despite these advantages, the usage of CPO-based biodiesel is still largely dependent on its ability to meet strict fuel-quality requirements. Biodiesel must comply with national and international standards, such as SNI 7182, to ensure safe storage, reliable engine operation, and compatibility with existing fuel distribution systems. Critical physicochemical parameters such as density, kinematic viscosity, CN, flash point, acid value, water content, and oxidative stability directly affect fuel injection behavior, atomization quality, ignition performance, combustion efficiency, corrosion tendency, and long-term storage stability [6]. One of these qualities is viscosity, which is particularly important since excessive viscosity can reduce fuel atomization efficiency, promote injector deposits, and degrade combustion performance. Flash point and oxidative stability are important indicators for fuel handling safety and resistance to deterioration during storage.

Therefore, enhancing CPO-based biodiesel's stability and quality continues to be a top research focus. To prevent unwanted changes in viscosity, acidity, volatility, and other fuel qualities during storage, post-treatment techniques, additive integration, and process optimization are necessary. To guarantee that CPO-derived biodiesel can attain standard-compliant quality while retaining its promise as a sustainable fuel alternative, rigorous optimization techniques are required [7].

Using adsorbents like bentonite during purification or post-treatment is another method to enhance the quality of biodiesel. Polar impurities, leftover free fatty acids (FFA), and other trace elements that negatively impact acidity, stability, and flash point can be eliminated with bentonite. Therefore, combining an oxygenated bio-additive with a solid adsorbent shows promise for improving the physicochemical and safety-related characteristics of biodiesel [8, 9].

Nevertheless, there aren't many systematic studies that combine bentonite-assisted pretreatment, citronella oil as an oxygenated bio-additive, and CPO-based biodiesel. Furthermore, it is yet unclear how additive content, bentonite loading, and treatment temperature combine to affect important fuel characteristics [10, 11].

The physicochemical characteristics of biodiesel, especially its viscosity, oxidation stability, and impurity concentration, have a significant impact on its quality. Fuel performance and storage stability can be adversely affected by residual impurities, including glycerol, FFA, and other polar substances. Because of its large surface area and potent adsorption capabilities, bentonite is added as an adsorbent to improve the purity, stability, and general fuel quality of biodiesel by removing unwanted contaminants.

Citronella oil is also included as a bio-based oxygenated additive to improve fuel stability and combustion properties. Citronellal, citronellol, and geraniol are among the oxygenated chemicals found in citronella oil that can enhance fuel atomization and encourage more thorough combustion. During storage, its inherent antioxidant qualities also aid in preventing oxidative deterioration. As a result, it is anticipated that using bentonite and citronella oil together will enhance the physicochemical characteristics of biodiesel, producing a cleaner, more stable, and superior sustainable fuel.

The goal of this research is to create and refine a two-step method for turning CPO into premium biodiesel. Base-catalyzed transesterification is the initial step in the production of biodiesel. The FFA level, viscosity, CN, and flash point are all improved in the second step by adding bentonite and citronella oil. The effects of bentonite loading and citronella oil concentration are examined using response surface methodology (RSM), and the resulting biodiesel's chemical makeup and functional groups are verified using gas chromatography–mass spectrometry (GC–MS) and Fourier-transform infrared spectroscopy (FTIR).

2. MATERIALS AND METHODS

2.1 Materials

PT. Sulthan Adidaya Industri Nusantara, Blok Petukel, Blang Jorong, Bener Meriah, Aceh Tengah, Aceh, Indonesia, provided the CPO and citronella oil. Throughout the studies, analytical-grade methanol, sodium hydroxide (NaOH), potassium hydroxide (KOH), phosphoric acid (H_3PO_4), bleaching earth, and deionized water were utilized. As an adsorbent, natural bentonite was utilized without any chemical alteration.

Table 1 shows the physical and chemical characteristics of CPO, which is the primary raw material. The deep orange-red hue, semi-solid physical state, moderate iodine value, and high concentration of bioactive substances, including carotenoids, tocopherols, and tocotrienols, are characteristics of CPO. The stability, melting behavior, and possible use of CPO in food, oleochemical, and biodiesel production are all determined by the fatty acid profile, especially the palmitic, oleic, and linoleic acids.

Table 2 displays the pertinent physical and chemical characteristics of citronella oil used as an ingredient in the biodiesel production process. Citronellal, geraniol, and citronellol are examples of oxygenated monoterpene chemicals found in citronella oil that can boost the fuel's oxygen availability and promote more thorough combustion. Citronella oil shows promise as a renewable low-dose bioadditive in biodiesel formulations based on its specific gravity, refractive index, flash point, and solubility properties.

Table 1. Physical and chemical properties of crude palm oil (CPO)

No.	Parameters	Result of Measurement
1	Free Fatty Acid (FFA)	≤ 5%
2	Moisture content	≤ 0.25%
3	Iodine value	50–55 g I_2/100 g oil
4	Density	0.89 – 0.92 g/cm³
5	Viscosity	40 - 47 cSt
6	Saponification value	190–205 mg KOH/g oil
7	Carotenoids	500–700 mg/kg
8	Vitamin E compounds	Tocopherols and tocotrienols
9	Major fatty acids	Palmitic, oleic, linoleic acids

Table 2. Citronella oil's chemical and physical characteristics

No.	Parameters	Result of Measurement
1	Specific gravity at 20 ℃	0.880 – 0.895
2	Refractive index at 20 ℃	1.466 – 1.473
3	Optical rotation at 20 ℃	-5° – 0°
4	Flash point	≥70 °C, typically >80 ℃
5	Citronellal	32–45 wt%
6	Geraniol	21–24 wt%
7	Citronellol	11–15 wt%
8	Geranyl acetate / Limonene	3–8 wt% / 1–4 wt%

2.2 Experimental facility

All experiments were carried out in the Chemical Engineering Teaching Factory at Politeknik Negeri Lhokseumawe. The pilot-scale installation consists of esterification and transesterification reactors equipped with mechanical agitation, heating via steam lines, vacuum drying units, washing tanks, storage tanks, and associated pumps and valves. Reaction temperature was controlled at 65 ℃ during transesterification, and agitation speed was set to ensure sufficient mixing and mass transfer between oil and methanol phases.

2.2.1 Synthesis of bentonite

During the dry season, bentonite samples were collected. The bentonite was collected, crushed into small particles, and dried for five days to facilitate crushing and sieving. It was then ground into a powder. X-ray fluorescence (XRF) analysis was used to determine the materials' chemical composition and to develop a spectrum that shows the relationship between intensity and energy. The bentonite composition was examined using XRF equipment, and the results are shown in Table 3.

Table 3. Chemical composition of bentonite based on X-ray fluorescence (XRF) analysis

No.	Oxide	Content (wt%)
1	SiO_2	49.95
2	Al_2O_3	30.70
3	Fe_2O_3	9.81
4	MgO	0.17
5	SO_3	0.31
6	P_2O_5	0.12
7	TiO_2	0.73
8	Mn_2O_3	0.37

XRF analysis was used to determine the chemical composition of the bentonite sample. The results show that bentonite is mostly composed of SiO_2 (49.95 wt%) and AlO_3 (30.70 wt%), indicating that it belongs to the aluminosilicate clay mineral group. The high silica and alumina content confirms the presence of silicate layers, which are often associated with montmorillonite-rich bentonite. This composition is consistent with previous studies that discovered that the main oxides in natural bentonite were SiO_2 and AlO_3, with trace amounts of FeO_3, MgO, TiO_2, and other metal oxides. Subsequently, modifications were made. North Aceh Regency was the source of the bentonite. After being dried at 105 °C and kept in a desiccator, the bentonite was partially separated to get a pure bentonite sample. The sample was then purified to obtain montmorillonite. Three steps are involved in the purifying process: centrifugation, dispersion, and grinding. After 60 minutes of grinding, the bentonite raw materials were sorted through a 230-mesh screen. 36 grams of free water were combined with 0.03 grams ($NaPO_3$), or 1% of the bentonite weight, to dissolve 3 grams of fine bentonite. After that, a magnetic stirrer was used to agitate the mixture for a whole day. Centrifuge for two minutes at 700 rpm after stirring. After that, the precipitate was dried to a constant weight in an oven at 60 °C. Additionally, the bentonite sample was modified to create organo-bentonite by adding cetyltrimethylammonium bromide (CTAB) as a surfactant.

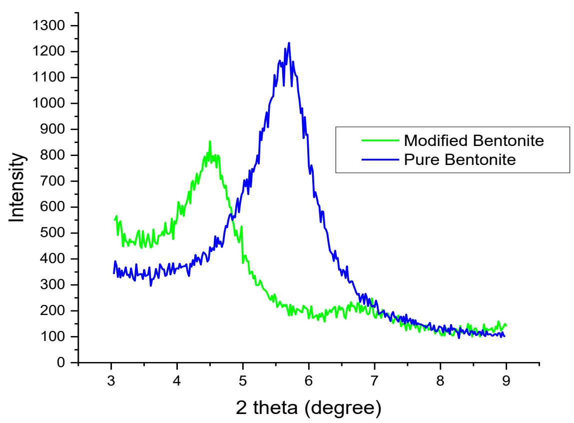


Figure 1. X-ray spectrum of pure bentonite and modified bentonite

The X-ray diffraction (XRD) test clearly shows the structural variations between treated and raw bentonite. The prominent and distinct diffraction peak in raw bentonite at about 2θ = 5.7–5.8° suggests that montmorillonite is the main clay component with a regular layered structure. As seen in Figure 1, upon modification, the major diffraction peak moves to a lower angle, around 2θ = 4.5–4.6°, and the peak intensity and peak width drop. This alteration shows that the bentonite's interlayer spacing has grown, suggesting that the modification method was successful in changing the clay's structure.

2.3 Biodiesel production from crude palm oil

The primary raw material used in the blending procedure with bentonite and citronella oil, which were produced by esterification and transesterification chemical chain reactions, was the CPO that was transformed into biodiesel. This procedure was completed in the Chemical Engineering Department's Biodiesel Production Teaching Factory laboratory at Lhokseumawe State Polytechnic. The primary raw material used in the blending procedure with bentonite and citronella oil, which were produced by esterification and transesterification chemical chain reactions, was the CPO that was transformed into biodiesel. This procedure was completed in the Chemical Engineering Department's Biodiesel Production Teaching Factory laboratory at Lhokseumawe State Polytechnic. A number of controlled processes, such as feedstock preparation, esterification, transesterification, glycerol separation, washing, vacuum drying, and final storage, are involved in the synthesis of biodiesel from palm oil. To guarantee a high conversion of triglycerides to FAME and to create biodiesel with optimum fuel quality, each stage needs particular operating conditions. The following are the general stages of the process: raw material preparation, esterification, transesterification, settling and glycerol separation, washing, vacuum drying, and final product storage.

2.3.1 Raw material preparation

Refined, bleached, deodorized palm oil (RBDPO), or palm oil feedstock, is heated and stored in the raw material tank before being transferred to the reactor during the preparation stage. The palm oil is heated to roughly 40 °C to improve flowability and reduce viscosity during pumping and mixing. Methoxide is prepared in the methoxide mixing tank, hot water is prepared in the hot water tank, and the steam system is activated simultaneously to heat the process equipment. At this stage, all of the systems—oil, methoxide, water, steam, and vacuum—must be ready to run continuously.

2.3.2 Esterification stage

The palm oil is transferred into the esterification reactor and heated by steam. The reactor temperature is maintained at about 65 °C with continuous stirring. At this stage, the reactor is filled with 500 L of methoxide and an acid catalyst. Esterification attempts to reduce the quantity of FFA by converting it into methyl esters. Throughout the process, an aqueous phase including gum, water, and impurities is produced and separated from the oil phase. This step is critical because a high concentration of FFA may result in soap formation and reduce the yield of biodiesel in the following stage. After a pre-esterification stage, base-catalyzed transesterification was used to produce biodiesel. CPO was first added to an esterification reactor and heated to roughly 65 °C while being constantly stirred. To transform FFA into esters, a methanol–acid catalyst mixture was added, and the reaction was allowed to continue for a predetermined amount of time. The impurity-containing aqueous phase was eliminated after settling [12].

2.3.3 Transesterification stage

After esterification, the treated oil is transferred into the transesterification reactor. More base catalyst and about 500 L of methoxide are added to the reactor. The reaction temperature is maintained at roughly 65 °C for 60 minutes with continuous mixing. At this point, triglycerides react with methanol in the presence of an alkaline catalyst, such as NaOH, to form FAME, which is biodiesel, and glycerol as a byproduct. Temperature, catalyst dosage, methanol concentration, and mixing time must all be carefully regulated to maximize ester conversion.

2.3.4 Settling and glycerol separation

After the transesterification reaction is complete, the mixture is allowed to settle for roughly sixty minutes. Because glycerol and biodiesel have differing densities, phase separation occurs during this settling phase. While the glycerol phase moves to the bottom, the crude biodiesel phase remains at the top layer. The glycerol is then drained and collected separately, and the crude biodiesel is transferred to the washing tank for further purification.

2.3.5 Washing process

The crude biodiesel still contains methanol, catalyst, soap, glycerol, and other impurities. It is therefore cleaned by giving it a hot water wash. Hot water uses up around half of the initial CPO volume. Steam is utilized to heat and mix the washing tank to improve the contact between biodiesel and water. After washing, the mixture is allowed to settle for about 30 minutes to separate the wastewater from the biodiesel layer. The wastewater is removed from the bottom while the cleaned biodiesel is transported to the drying unit.

2.3.6 Vacuum drying process

The cleaned biodiesel is dried using a vacuum drying evaporator. In this phase, any residual water in the biodiesel is evaporatively removed using suction. Steam is supplied to the evaporator to help with drying, while the suction system helps decrease the water's evaporation point. The drying cycle is critical because residual water in biodiesel can reduce fuel stability, promote microbial growth, and cause corrosion during storage or engine operation.

2.3.7 Final product storage

After drying, the final product—purified biodiesel—is transferred into the biodiesel storage tank. At this stage, the biodiesel should be free of excess water, residual catalyst, methanol, soap, and glycerol. To create biodiesel with stable quality and appropriate fuel qualities, FAME is blended with bentonite and citronella oil. The biodiesel yield was carefully computed using the mathematical model described in Eq. (1) to measure the effectiveness of the transesterification process. This analytical framework ensures great accuracy in our performance evaluation by taking into consideration the mass balance of the finished product and the stoichiometric ratio of reactants. A significant biodiesel production of 84% was attained once the computation based on the experimental data was completed. This outcome shows that the reaction conditions successfully changed the equilibrium toward the synthesis of FAME, demonstrating the effectiveness of the suggested operating parameters.

$$Yield\ (\%) = \frac{litres\ of\ biodiesel\ yield}{litres\ of\ crude\ palm\ oil} \times 100\% \quad (1)$$

2.4 Blending with citronella oil and bentonite

To enhance fuel quality and safety, biodiesel and citronella oil were combined in the second stage while bentonite was present. A stirring vessel was filled with 150 mL of dried biodiesel for each experiment. The experimental design called for the addition of bentonite (0.75, 0.80, 0.85, and 0.90 g) and citronella oil (4, 6, 8, and 10 mL). The mixture was heated to 65 °C and stirred for 60 minutes at 500 rpm. A systematic workflow detailing the blending process of biodiesel with bentonite and citronella oil can be seen in Figure 2.

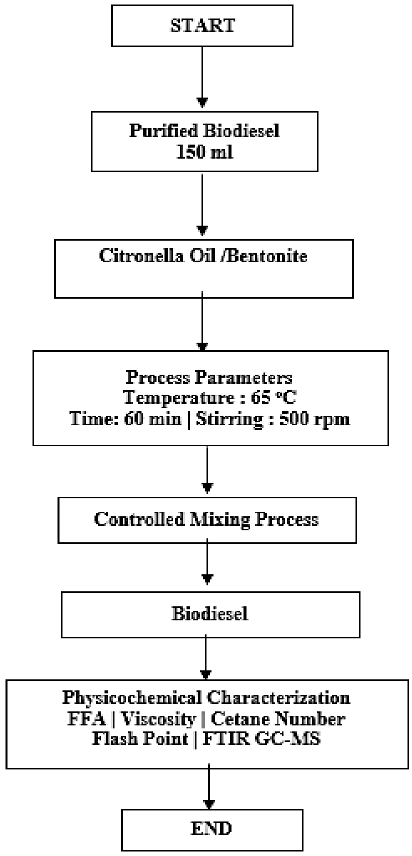


Figure 2. Schematic diagram of the biodiesel-bentonite-citronella oil blending process

The liquid was blended, allowed to settle, and then filtered to get rid of bentonite particles. The blend of transparent biodiesel and citronella oil was gathered for physicochemical analysis. Based on biodiesel, the concentration of citronella oil in the wider optimization region was between 10 and 14 weight percent. The values were compared with relevant fuel specifications (e.g., SNI 7182-2015 for diesel fuel) to assess suitability for engine application and storage safety.

2.5 Gas chromatography–mass spectrometry analysis

GC–MS was used to analyze the most promising biodiesel sample, which was made with 0.85 g bentonite and 10 mL citronella oil in accordance with ASTM D5769. A capillary column was used for the chromatographic separation, and mass spectra were captured to identify the compounds. Major FAME components and other chemicals were identified by comparing retention periods and mass fragmentation patterns with standard libraries.

2.6 Fourier-transform infrared spectroscopy analysis

Functional groups in bentonite, citronella oil, and biodiesel were examined using FTIR spectroscopy. Mid-infrared scanning of the samples produced distinctive bands linked to hydroxyl, carbonyl, and C–H stretching and bending vibrations. Bands associated with Si–O–Si, Al–O–Si, and structural hydroxyl groups were examined for bentonite. Ester carbonyl (C=O) and alkyl chain (C–H) bands were utilized to demonstrate successful transesterification in biodiesel.

2.7 Statistical analysis and response surface methodology

The effects of temperature, bentonite loading, and citronella oil concentration on responses such as FFA content, viscosity, CN, and flash point were assessed using RSM. To see how the variables interacted, two-dimensional (2D) contour plots and three-dimensional (3D) surface plots were created. Pareto charts were utilized to enhance the optimization of biodiesel quality and to determine the most important factors influencing each response.

3. RESULTS AND DISCUSSION

The physicochemical characteristics of the biodiesel purified under varying operating conditions—specifically Bentonite dosages (0.75–0.90 g) and citronella oil volumes (4–10 mL)—are summarized in Table 4. The experimental data reveal a significant correlation between adsorbent concentration and the reduction of impurities within the biodiesel matrix. The optimal purification efficiency was observed at a bentonite dosage of 0.90 g combined with 10 mL of citronella oil, which yielded a minimum FFA content of 0.24%. This result, coupled with a kinematic viscosity of 3.2 cSt, a CN of 64.6, and a flash point of 112 °C, confirms that the purified product strictly adheres to the established SNI 7182-2015 standards (Table 5). These findings suggest that higher Bentonite concentrations, when synergized with the solvent properties of citronella oil, effectively enhance mass transfer kinetics and the adsorption of polar impurities, thereby playing a critical role in stabilizing the biodiesel against oxidative degradation.

Table 4. Physicochemical characteristics of biodiesel under different operating conditions

Bentonite (g)	Citronella Oil (mL)	Free Fatty Acid (FFA) (%)	Viscosity (cSt)	Cetane Number (CN)	Flash Point (°C)
0.75	4	0.47	4.2	66.3	104
	6	0.48	4.6	63.6	102
	8	0.55	3.4	64.6	106
	10	0.47	3.6	62.3	107
0.80	4	0.52	3.7	65.7	103
	6	0.43	3.7	64.5	104
	8	0.48	4.2	64.8	106
	10	0.51	4.6	63.4	108
0.85	4	0.43	4.8	68.1	107
	6	0.32	4.1	67.5	102
	8	0.26	3.7	66.2	108
	10	0,25	3.6	66.9	109
0.90	4	0.4	4.3	64.1	104
	6	0.46	4.4	57.9	106
	8	0.43	4.3	65.9	101
	10	0.24	3.2	64.6	112

Table 5. Comparison of the physicochemical properties of the produced biodiesel with the SNI 7182-2015 standards

No.	Characteristic	SNI 7182-2015
1	Density (kg/m^3)	850-890
2	Flash point (°C)	Min 100
3	Kinematic viscosity (cSt)	2.3-6.0
4	Cetane number (CN)	51
5	Acid value (mg KOH/g)	Max 0.5

3.1 Effect of citronella oil and bentonite on free fatty acid

In order to guarantee engine compatibility and long-term stability, crude biodiesel must be purified. The combination of bentonite (a phyllosilicate clay) with citronella oil (a source of vital chemicals, mainly citronellal) produces a synergistic adsorption environment that dramatically reduces the amount of FFA. A multi-mechanism adsorption process is responsible for the lowering of FFA levels from 0.55% to an ideal 0.24% at 0.90 g of bentonite and 10 mL of citronella oil. Bentonite is a naturally occurring clay mineral with a net negative charge on its structural layers and a large surface area. As a result, a strong cation exchange capacity is produced. Through physisorption and chemisorption, the acidic FFA molecules are drawn to the active sites on the Bentonite surface and become trapped there. The direct relationship between larger Bentonite mass and lower residual FFA can be explained by the fact that more surface area becomes available as the dosage increases. Citronella oil functions as a chemical modifier in addition to being a diluent. The oil's oxygenated monoterpenes help long-chain fatty acids dissolve, lowering their viscosity and increasing their accessibility to the Bentonite's porous structure. Additionally, the oil facilitates improved interaction between the adsorbent and the contaminants scattered throughout the biodiesel matrix by reducing the interfacial tension.

According to other publications on the use of clay-based adsorbents and oxygenated bio-additives for eliminating polar contaminants and FFA in biodiesel systems [8], this trend suggests that increasing both bentonite dose and citronella oil addition can successfully lower acidity. Citronella oil may help with dilution and better interactions during adsorption, while bentonite serves as an adsorbent for polar contaminants and leftover acids [13].

3.2 Kinematic viscosity analysis

One important factor affecting the atomization and injection properties of diesel engines is kinematic viscosity. The generated biodiesel's observed viscosity values varied from 3.2 to 4.8 cSt. The viscosity values obtained from all experimental configurations are within the SNI 7182-2015 range of 2.3–6.0 cSt. This consistency implies that the fuel retains its ideal fluid properties for engine operation even if the purification procedure is successful in eliminating acidic contaminants without negatively changing the base molecular structure of the FAME. This success is largely due to the use of bentonite as a solid adsorbent; its high surface area and porous structure enable the selective removal of polar contaminants and FFAs, which could otherwise cause oxidative instability or unintentional viscosity changes. At the same time, citronella oil is added as a functional oxygenated additive that helps maintain the fuel's thermodynamic stability while also improving its volatility properties without affecting flow dynamics. The viscosity stability that mimics proven CPO-based biodiesel performance shows that these treatments do not damage the structural integrity of the FAME [14]. By demonstrating that the fuel maintains the exact rheological window necessary for efficient combustion, this synthesis of bentonite-driven purification and citronella-based enrichment reduces the hazards of incomplete combustion and long-term mechanical deterioration of high-pressure injection systems.

Similar to ranges reported for CPO-based biodiesel and other oxygenated additives, viscosities generally stayed within standard biodiesel limits, suggesting that the addition of citronella oil and the application of bentonite treatment did not negatively alter flow behavior [14]. For diesel engines to properly atomize, inject, and mix fuel, moderate viscosities are necessary. This stability is primarily attributed to the dual functionality of the post-synthesis treatment. First, the application of bentonite acts as an advanced solid-phase adsorbent, utilizing its hierarchical pore structure to selectively sequester FFAs and polar impurities. As highlighted by recent studies on sustainable purification techniques, such mineral-based treatment is superior in refining biodiesel quality without inducing the thermal degradation often associated with conventional washing processes. The process proceeds more effectively, reducing soap production and enhancing biodiesel separation, when FFA is lowered to a lower level prior to transesterification; better stability, clearer phase separation, and viscosity values that meet the needs of biodiesel fuel are thus possible for the finished fuel [15].

At the blending coordinate of 0.80 g bentonite and 10 mL citronella oil, a significant rheological anomaly was detected, where the kinematic viscosity peaked at 4.6 cSt. This divergence reflects a delicate balance between changes in the fuel matrix's adsorptive equilibrium and swelling-induced structural network development. At a moderate dosage of 0.80 g bentonite, the quantity of oxygenated monoterpenes localized in the swelling of the aluminosilicate layer is caused by the 10 mL of citronella oil acting as a solvent that readily enters the bentonite interlayer galleries. The observed viscosity spike is caused by this expansion, which significantly raises the effective volume fraction of the dispersed solid phase and creates a transient, extremely cohesive structural network that traps fluid molecules and macroscopically limits mobility. Conversely, when the solid-phase concentration is boosted further to 0.85 g and 0.90 g, the system undergoes an adsorptive collapse phase. There are deep bent bent bent bent bent bent surface surface shifts that actively actively actively actively actively actively actively actively actively. A refined, highly purified FAME profile with standardized, noticeably reduced viscosities of 3.6 cSt and 3.2 cSt, respectively, is produced by this technique, which totally collapses the transient structural network.

3.3 Cetane number and ignition quality

The CN serves as a measure of the fuel's ignition delay period; a higher value signifies superior ignition quality. The experimental biodiesel demonstrated a range of CNs from 57.9 to 68.1. These results consistently surpass the minimum threshold of 51 mandated by SNI 7182-2015. The high cetane values obtained are promising, as they correlate with improved combustion efficiency, reduced ignition delay, and potentially lower levels of NO_x emissions during high-load engine operation.

The CN was used to assess the ignition quality of the produced biodiesel, and the results showed a strong range of 57.9 to 68.1. These results significantly surpass the SNI 7182-2015 minimum criterion of 51, indicating exceptional auto-ignition capability. The synergistic effects of the purification and additive techniques used are essential to achieving these high CN values. Bentonite is a solid-phase adsorbent that efficiently reduces moisture and long-chain polar chemical concentrations. This promotes a more advantageous distribution of saturated fatty acid chains, which is necessary for shorter ignition delays.

Additionally, the incorporation of citronella oil greatly improves the igniting properties. According to recent research, the oxygenated terpenes in citronella oil affect the radical branching processes that occur during the pre-combustion stage, acting as ignition promoters. By accelerating the transition from the ignition delay period to the premixed combustion phase, this chemical change improves overall thermal efficiency and reduces the production of NO_x under high-load circumstances. Overall, these cetane figures validate the good ignition behavior of CPO-based biodiesel and compare favorably with traditional diesel fuels [16].

3.4 Flash point and safety standards

A key safety metric is the flash point, which is the temperature at which the fuel releases enough vapor to create an ignitable combination. The purified samples' reported flash points ranged from 101 °C to 112 °C. These values meet the minimum 100 °C safety requirement for biodiesel. The steady achievement of these flash points indicates that the purification procedure has eliminated volatile impurities, particularly low-molecular-weight alcohols or leftover reaction components, improving the final product's safe handling and storage qualities.

The flash point of the synthesized biodiesel samples was recorded in the range of 101 °C to 112 °C, consistently surpassing the minimum safety threshold of 100 °C established by the SNI 7182-2015 standard. This compliance is a direct outcome of the rigorous purification strategy, where bentonite functions as a critical adsorbent for low-molecular-weight volatile organic compounds (VOCs) and residual methanol impurities notorious for depressing flash point values. According to recent safety and quality assessments in biofuel processing, the effective removal of these volatile contaminants via solid-phase adsorption is essential for ensuring operational safety during fuel storage and transport.

Furthermore, the introduction of citronella oil as an additive did not negatively impact this thermal safety profile. On the contrary, the presence of heavier oxygenated terpenes within the oil contributes to a stable vapor pressure, preventing the fuel from reaching an ignitable mixture at lower temperatures. This maintenance of a high flash point, coupled with the absence of residual reactants, confirms that the proposed production process yields a product with superior handling characteristics, mitigating the risks associated with fuel volatility and ensuring institutional safety standards are strictly upheld.

The improvement in flash point as compared to the original biodiesel product indicates that bentonite treatment and blending were successful in eliminating volatile components, such as residual methanol. However, several formulations continue to be near the minimum specification, suggesting that additional drying and additive level adjustment would be advantageous. The lowest temperature at which fuel vapor can ignite in the presence of an ignition source is known as the flash point. While a low flash point frequently suggests the existence of residual methanol or other volatile chemicals in biodiesel, a higher flash point enhances safety during handling, storage, and transportation [17, 18]. Both ignition quality and safety must be taken into account while optimizing processes, according to the combined analysis of CN and flash point.

3.5 Pareto analysis of process variables

The relative contributions of bentonite loading and citronella oil content are shown in Pareto charts for viscosity and flash point. For both cases, citronella oil loading seems to be the most important factor. In terms of viscosity, the removal of polar and low-molecular-weight components is greatly impacted by an increase in citronella oil loading. Depending on how adsorption and the removal of light fractions are balanced, this can either slightly enhance or decrease viscosity. Citronella oil has a significant impact on the residual content of volatile chemicals in terms of flash point; greater dosages of citronella oil often remove more volatiles and raise flash point

The Pareto chart analysis illustrates the relative contributions of bentonite loading and citronella oil content to the final product viscosity. The data identifies citronella oil loading as the most statistically significant factor influencing the viscosity profile, as it uniquely exceeds the established Bonferroni limit. Mechanistically, an increase in citronella oil dosage plays a critical role in the removal of polar and low-molecular-weight components. Consequently, the resulting viscosity is subject to a complex balance between the adsorption process and the removal of light fractions, which can result in either a slight enhancement or a decrease in overall viscosity. These findings underscore the importance of precision in controlling citronella oil concentration, as it similarly exerts a significant impact on the residual volatile chemicals and subsequent flash point characteristics of the formulation

Beyond rheological properties, the dosage of citronella oil serves as a vital control for safety and stability metrics. The oil plays a significant role in managing the residual content of volatile chemicals. Consequently, higher dosages of citronella oil are consistently correlated with the effective removal of these volatiles, which directly leads to an increase in the flash point of the product. These findings underscore the necessity of precision-based control of citronella oil concentration, as it acts as a dual-action agent that modulates both the physical viscosity and the volatile profile of the formulation. The considerable adsorption capacity of bentonite toward polar contaminants, residual methanol, moisture, catalyst residues, and FFA explains the dominance of bentonite loading from a Pareto perspective. These elements are directly linked to the instability and subpar safety properties of biodiesel. More active adsorption sites become accessible when bentonite dosage rises, making it possible to remove unwanted substances more successfully. As a result, the biodiesel's physicochemical structure becomes cleaner and more stable, which explains bentonite's significant contribution to both flash point improvement and viscosity reduction/control, which has been extensively highlighted in recent biodiesel research [1, 10, 19, 20].

According to Figure 3 and Figure 4, Pareto analysis, the most important factor influencing the quality of biodiesel is citronella oil concentration, which is followed by citronella oil concentration and process temperature. This pattern demonstrates how important the purification phase is for regulating both kinematic viscosity and flash point. After transesterification, residual contaminants, moisture, FFA, soap, catalyst residues, and volatile chemicals can all be reduced by using bentonite as an adsorbent. This interpretation, which claims that bentonite contributes most to viscosity variance and flash point improvement, is also consistent.

The major influence of bentonite on kinematic viscosity indicates that consistent fuel-flow behavior requires an appropriate adsorbent dose. While high viscosity can result in poor atomization, incomplete combustion, and injector deposits, acceptable viscosity promotes good atomization, injection, and air-fuel mixing in diesel engines. In order to produce biodiesel with appropriate flow properties, adjusting the dosage of bentonite is crucial.

Because of its inherent volatility and oxygenated chemical makeup, the concentration of citronella oil has a secondary but substantial effect, particularly on flash point. Within the studied range, temperature has a minor impact on mixing efficiency and adsorption kinetics, but it has little effect on the final fuel attributes. The considerable adsorption capacity of bentonite toward polar contaminants, residual methanol, moisture, catalyst residues, and FFA explains the dominance of bentonite loading from a Pareto perspective. These elements are directly linked to the instability and subpar safety properties of biodiesel. More active adsorption sites become accessible when bentonite dosage rises, making it possible to remove unwanted substances more successfully. As a result, the biodiesel's physicochemical structure becomes cleaner and more stable, which explains bentonite's significant contribution to both flash point improvement and viscosity reduction/control. In recent biodiesel research, solid adsorbents and catalytic solid materials have played a significant role in the purification and upgrading of biodiesel [10, 19, 20].

These results imply that to obtain the desired combination of viscosity and flash point, accurate control of bentonite dosage and suitable selection of citronella oil concentration are essential. From the analysis of the Pareto diagram in Figures 3 and 4, it is clear that the concentration of bentonite has a significant effect on the quality of biodiesel in terms of viscosity and flash point values.

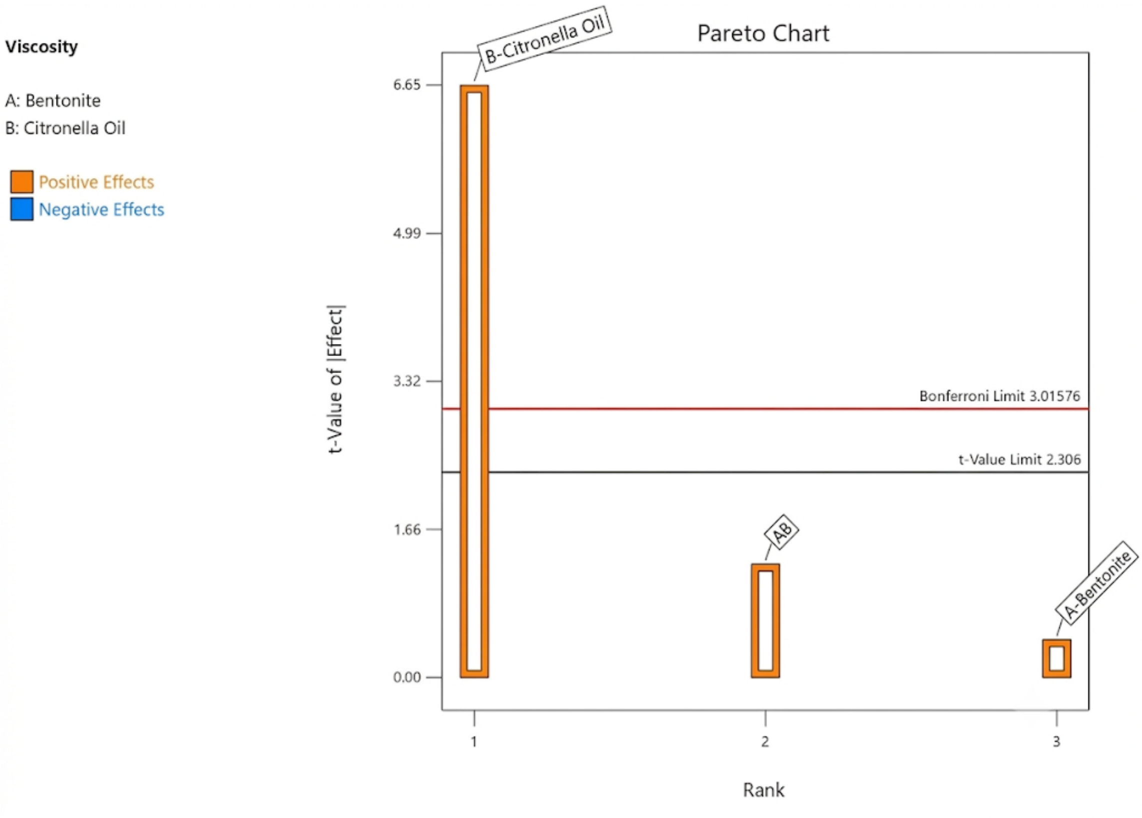


Figure 3. Pareto charts of standardized effects for kinematic viscosity of biodiesel

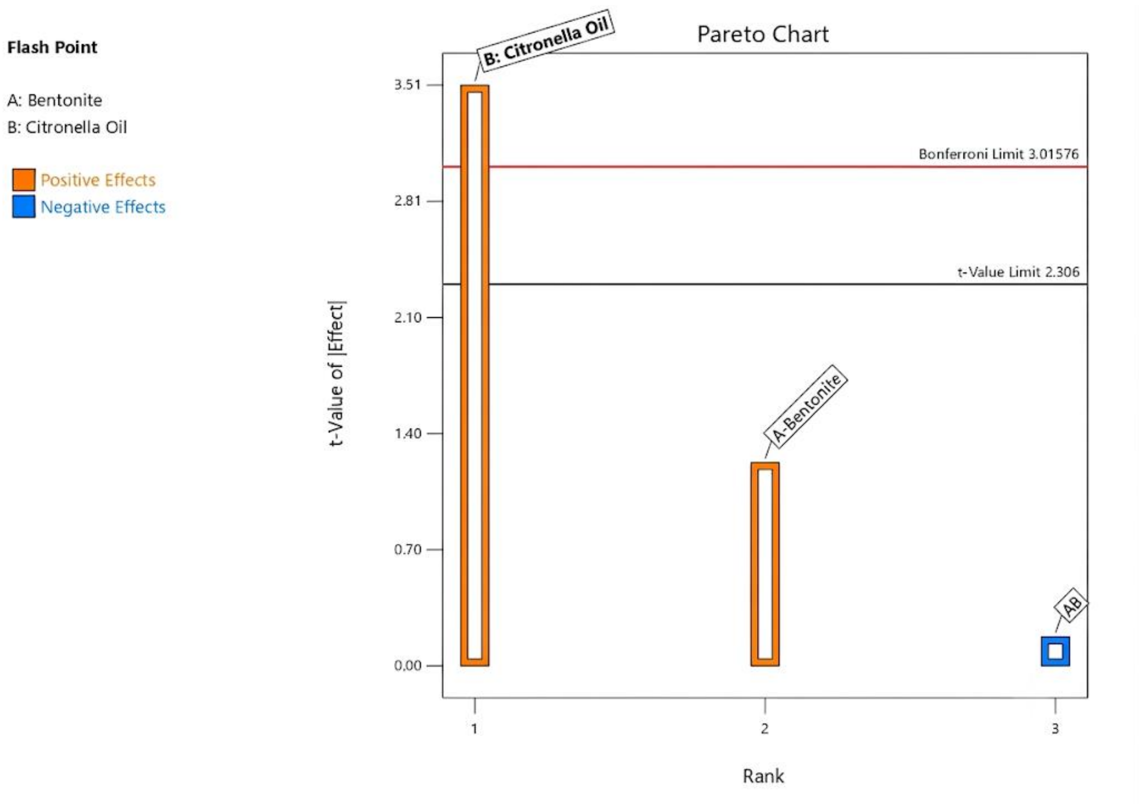


Figure 4. Pareto charts of standardized effects for the flash point of biodiesel

3.6 Analysis of variance

RSM was used to systematically assess the optimization of biodiesel fuel attributes, particularly FFA content, viscosity, CN, and flash point. Analysis of variance (ANOVA) was used to thoroughly validate the empirical relationship created by the experimental design matrix (Table 6) to guarantee its mathematical sufficiency and predictive dependability.

The biodiesel's FFA, viscosity, CN, and flash point were optimized using ANOVA, with the findings displayed in Table 7. While the interacting effects AB are significant, the main effects of citronella oil (A) and bentonite (B) are linearly represented and statistically significant.

To assess the statistical significance and fitness of the model equation, ANOVA was used. The chosen response's impact on significant individual variable and their relationship was also examined by ANOVA. Table 7 displays these outcomes. Due to the greater F-value (15.33) and lower *p*-value (0.0011), the results demonstrate that the model is highly significant at the 95% confidence level. When evaluating the significance of each regression coefficient, the *p*-value, which expresses the chance of error, is utilized. The *p*-value also reveals how each cross-product interacts with the others. A big F-value resulting from noise has a 0.01%chance of occurring, according to the *p*-value of 0.0011. In this instance, the generation of biodiesel is significantly influenced by A (citronella oil) and B (bentonite). Due to its larger F-value (44.18) and lower *p*-value (0.0002), A (citronella oil) is the most significant variable in the production of biodiesel from CPO. In this work, the R^2 statistics, consisting of the coefficient of determination (R^2) and adjusted R^2, have been applied to explain the models; an R^2 value of over 80% is usually considered significant. As presented in Table 7, the values of R^2 were obtained to be 0.8533 and 0.8221 for the CR models, respectively, which emphasizes that the developed models could explain 85.33 and 82.21% of the response variance.

Table 6. Response surface methodology (RSM) design matrix and experimental results

Run	Factor A: Citronella Oil (mL)	Factor B: Bentonite (g)	Response 1: Free Fatty Acid (FFA) (%)	Response 2: Viscosity (cSt)	Response 3: Cetane Number (CN)	Response 4: Flash Point (°C)
1	4	0.75	0.47	4.2	66.3	104
2	6	0.75	0.48	4.6	63.6	102
3	8	0.75	0.55	3.4	64.6	106
4	10	0.75	0.47	3.6	62.3	107
5	4	0.80	0.52	3.7	65.7	103
6	6	0.80	0.43	3.7	64.5	104
7	8	0.80	0.48	4.2	64.8	106
8	10	0.80	0.51	4.6	63.4	108
9	4	0.85	0.43	4.8	68.1	107
10	6	0.85	0.32	4.1	67.5	102
11	8	0.85	0.26	3.7	66.2	108
12	10	0.85	0.25	3.6	66.9	109
13	4	0.90	0.40	4.3	64.1	104
14	6	0.90	0.46	4.4	57.9	106
15	8	0.90	0.43	4.3	65.9	101
16	10	0.90	0.24	3.2	64.6	112

Table 7. Analysis of variance (ANOVA) for the experimental results of biodiesel

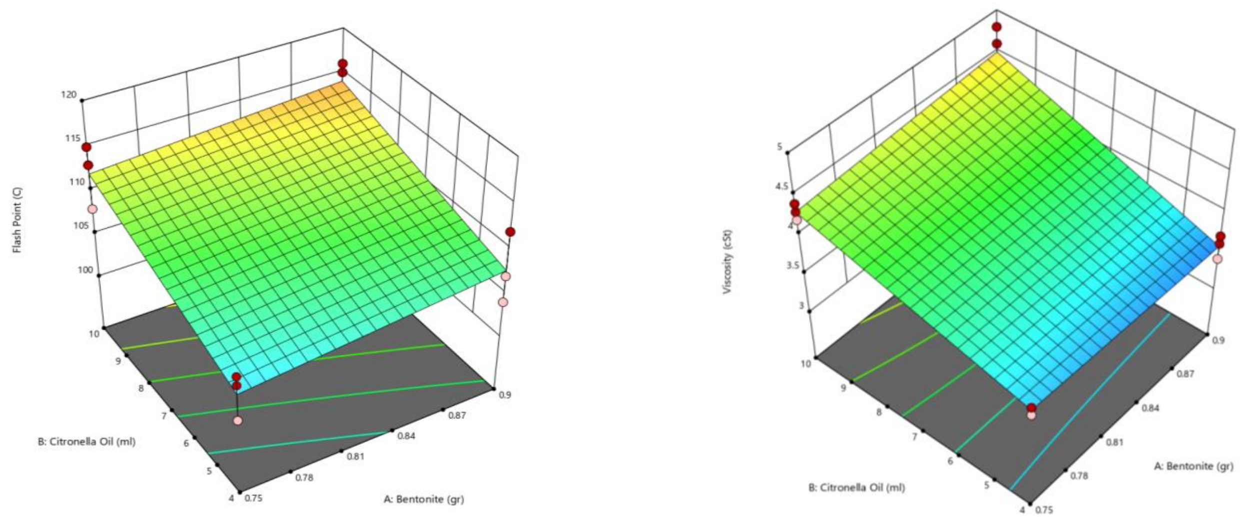
Source	Sum of Squares	Df	Mean Square	F-Value	*p*-Value	Remark
Model	1.92	3	0.6386	15.33	0.0011	Significant
A-Citronella Oil	1.84	1	1.84	44.18	0.0002	
B-Bentonite	0.0075	1	0.0075	0.1800	0.6826	
AB	0.0675	1	0.0675	1.62	0.2388	
Pure Error	0.3333	8	0.0417			
Total	2.25	11				
R^2 (unitless)	0.8533					
Adjusted-R^2 (unitless)	0.8221					

3.7 Response surface analysis

The interactive effects of bentonite loading (g) and citronella oil concentration (mL) on the physicochemical quality of the resultant biodiesel were assessed and optimized in this study using RSM, with a particular focus on kinematic viscosity and flash point. Plotting 3D surface curves against two independent variables while keeping other parameters at their central values allows the RSM approach to map the effects of process factors on transesterification efficiency. The final properties of the biodiesel are largely determined by the interaction between bentonite and citronella oil. These parameters were chosen because they are important for fuel performance: kinematic viscosity affects fuel atomization, spray penetration, injection behavior, and engine combustion efficiency, while flash point represents fuel volatility, residual alcohol content, and storage safety. The 3D response surface and 2D contour plots showing the interactive effects of bentonite and citronella oil concentrations at particular fixed parameters are shown in Figure 5. The graphical optimization shows that the fundamental characteristics of the produced biodiesel are greatly improved by a larger weight percentage of citronella oil. In particular, using the highest quantity of citronella oil results in an ideal fuel profile with a high flash point of 112 °C and a kinematic viscosity of 4.4 cSt.These findings highlight how crucial citronella oil loading is to refining gasoline quality in order to satisfy strict international standards.

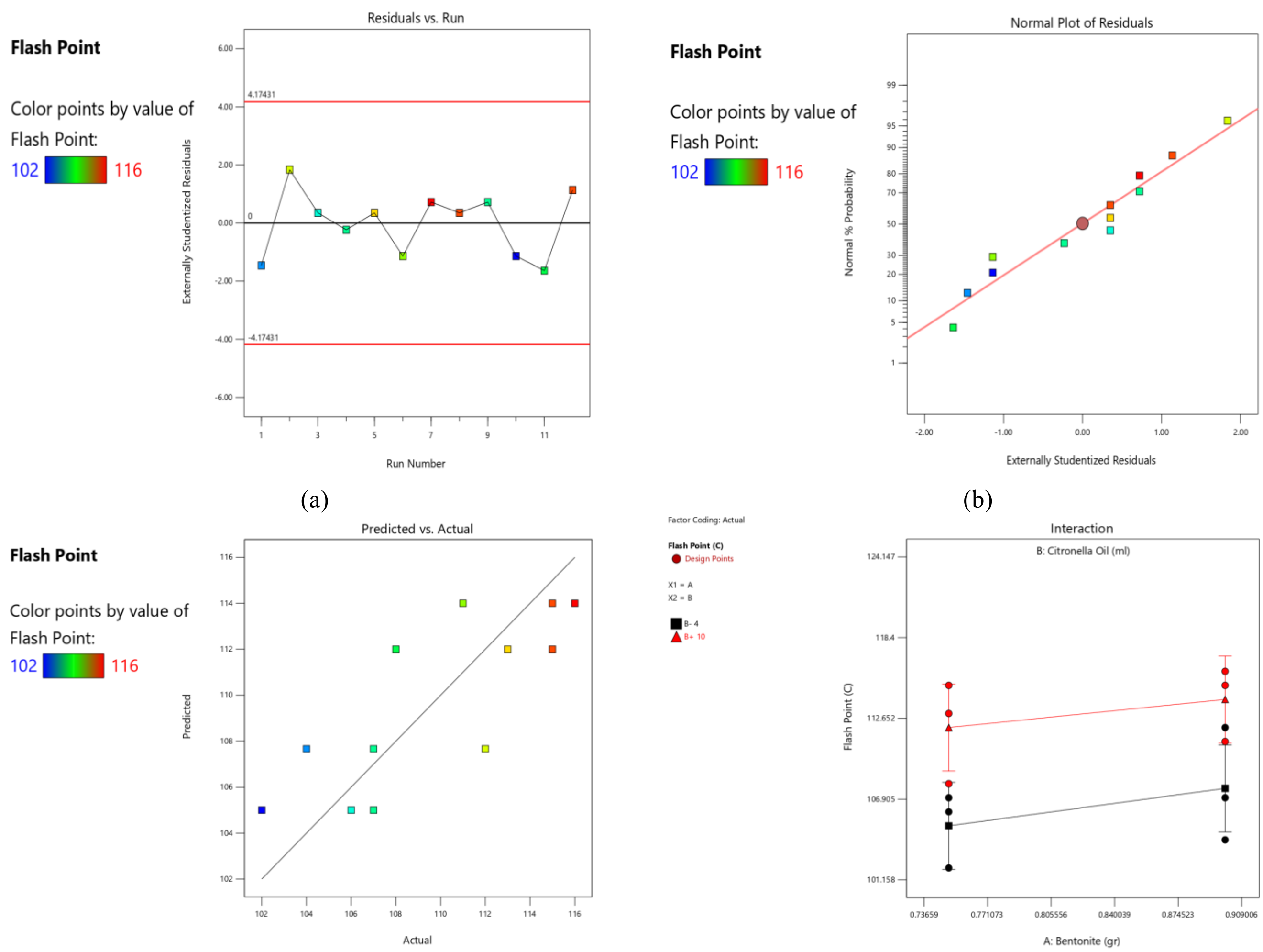
The combined effects of bentonite loading and citronella oil content on the physicochemical quality of the generated biodiesel, namely kinematic viscosity and flash point, were assessed using RSM. These two responses are crucial because, while flash point represents fuel volatility, residual alcohol content, storage safety, and handling characteristics, viscosity influences fuel atomization, spray penetration, injection behavior, and combustion efficiency [21]. Recent research on biodiesel further highlights the significant influence of feedstock composition, purification efficiency, catalyst residue, and additive formulation on fuel qualities [22].

The 3D response surface plots demonstrate that variations in biodiesel quality were influenced by the proportion of both bentonite and citronella oil. Bentonite primarily served as an adsorptive purification material, assisting in the elimination of water, soap, FFA, polar impurities, residual catalyst, and trace pollutants. This view is consistent with previous research demonstrating that adsorption-based purification can enhance the quality of biodiesel by lowering contaminants and requiring fewer intensive wet-washing procedures. As a bio-based addition, citronella oil influenced alterations in combustion-related characteristics and volatility. According to reports, one possible method for altering fuel behavior in compression-ignition engines is the use of fuel components obtained from citronella [23].



(a) (b)

Figure 5. Two-dimensional (2D) response contour plots and three-dimensional (3D) response surface plots for the effects of (a) bentonite and (b) citronella oil on biodiesel flash point and viscosity



(a) (b)

(c) (d)

Figure 6. Diagnostic plots for (a) plot for residual vs run, (b) normal plot for residuals, (c) predicted vs actual, and (d) interaction for flash point

The synthesis of biodiesel using bentonite as a catalytic support and citronella oil as a functional additive involves complex physicochemical interactions that dictate fuel quality. Bentonite acts as an effective heterogeneous catalyst, where its high surface area and porous structure provide abundant active sites that facilitate the transesterification process and enhance conversion efficiency. Furthermore, its role as an adsorbent during the purification phase removes soap, residual water, and polar impurities, creating a cleaner reaction environment that directly ensures the stability of both kinematic viscosity and flash point. Simultaneously, citronella oil functions as a critical additive that modulates kinematic viscosity by reducing intermolecular forces, while its presence promotes the removal of residual alcohols and low-boiling-point impurities, thereby refining the fuel's flash point. Ultimately, the synergistic combination of bentonite-assisted transesterification and citronella oil formulation optimizes the fuel profile, ensuring the final product meets stringent international quality standards.

3.7.1 Diagnostic plots

Additional plots were utilized to assess the model's suitability and determine whether the model equation would produce accurate approximations of the real value. Moreover, Figure 6 demonstrates the close correspondence between the anticipated values and the experimental results. These also show how the model may be used to forecast the ideal circumstances for the transesterification process's highest possible biodiesel yield. The externally studentized residuals plot was created to represent the model's fitness and demonstrate that all the data points lie within the limits of (±2). The normal probability plot of residuals for biodiesel production is continuously distributed.

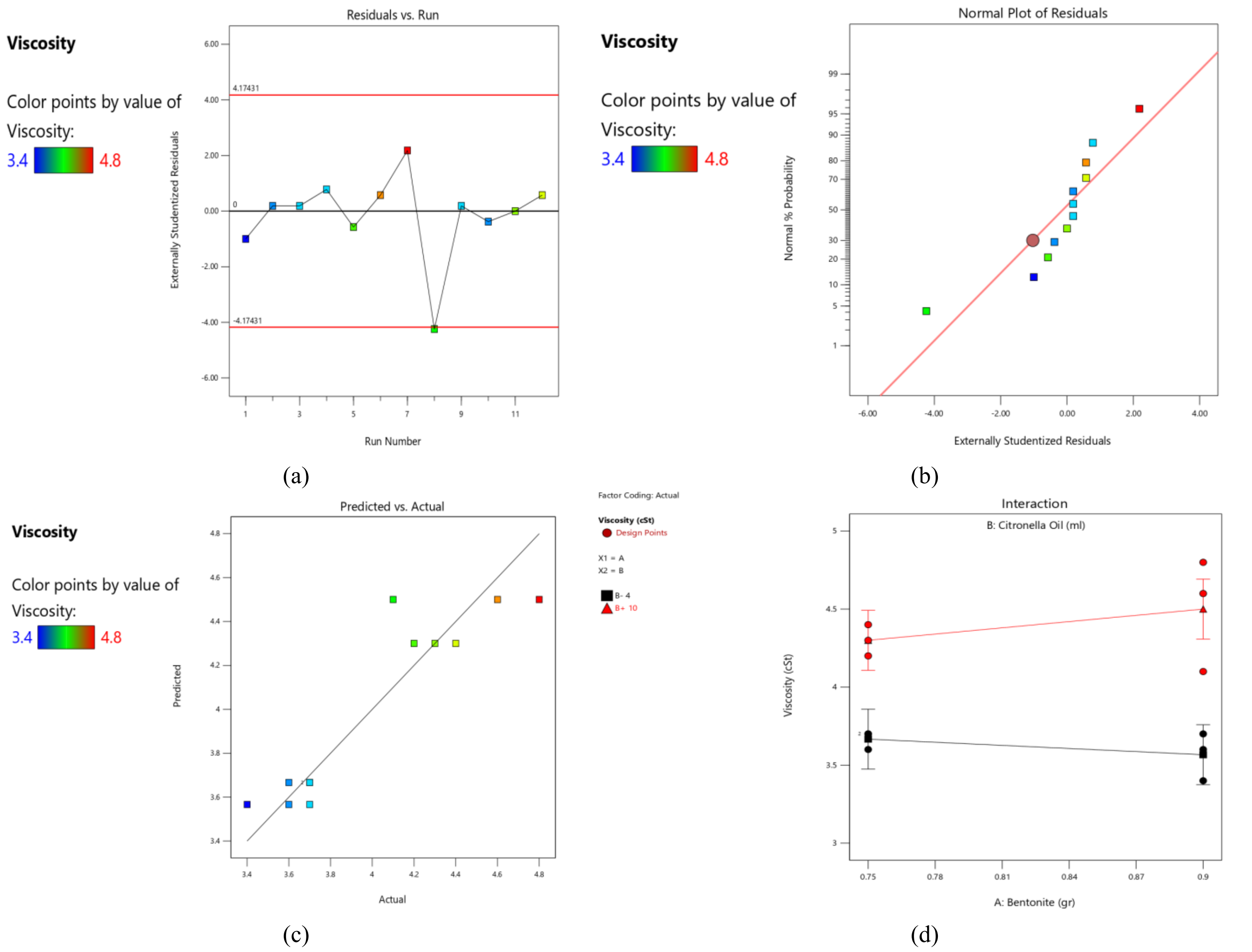


Figure 7. Diagnostic plots for (a) plot for residual vs run, (b) normal plot for residuals, (c) predicted vs actual, (d) interaction for viscosity

Figures 6 and 7 illustrate how thorough diagnostic plots were assessed to fully confirm the empirical model's forecast accuracy for the formulation's flash point. The robustness of the model is further reinforced by externally studentized residuals staying tightly within control limits, a linear normal probability distribution showing constant variance, and a good correlation between predicted and actual values. Importantly, interaction analysis shows that the synergy between the two main factors greatly influences thermal stability; raising the concentration of citronella oil significantly raises the flash point, and gradually adding bentonite further improves this thermal safety profile, demonstrating the model's dependability for process optimization.

To evaluate the empirical model's adequacy and determine whether the equation produces accurate approximations of the real system, comprehensive diagnostic plots were thoroughly analyzed for formulation viscosity. The strong correlation between the predicted and actual values (3.4–4.8 cSt) demonstrates a close correspondence that validates the model's robust capability to forecast ideal operational conditions. This structural fitness is verified by the diagnostic plot of externally studentized residuals vs. run, which proves that all experimental data points lie securely within the designated control limits of ±4.17431 without any abnormal patterns. Furthermore, the continuous, straight-line distribution in the normal % probability plot confirms that the experimental errors are normally distributed and the variance is perfectly stable. Crucially, this diagnosed stability underpins the interaction analysis, which reveals that fluid viscosity is highly dependent on the synergistic effects between bentonite and citronella oil; at a low oil volume (4 mL), increasing the bentonite concentration (0.75 to 0.9 g) maintains a stable, lower viscosity of approximately 3.6 cSt, whereas at a high oil volume (10 mL), it triggers a sharp upward trend reaching a maximum of around 4.5 cSt due to swelling-induced structural network formation.

3.8 Gas chromatography–mass spectrometry characterization

A Shimadzu 2010 Plus gas chromatograph equipped with a 30-meter-long DB-23 Agilent column was used to evaluate the purified biodiesel. To measure the ester content, nitrogen (N_2) was used as the carrier gas, and the detector temperature was set at 350 °C. Figure 8 and Table 8 display the GC–MS chromatogram of the biodiesel sample using 0.90 g bentonite and 10 mL citronella oil.

To confirm the chemical transformation of CPO into biodiesel and to determine the predominant FAME compounds generated during transesterification, GC–MS analysis was employed. The efficient conversion of the triglyceride fraction of CPO into biodiesel was confirmed by the chromatographic profile, which displayed multiple main peaks corresponding to methyl ester derivatives of C16–C18 fatty acids. This view is in line with previous biodiesel research showing that GC–MS is a dependable technique for determining FAME production and assessing the composition of biodiesel following transesterification [24].

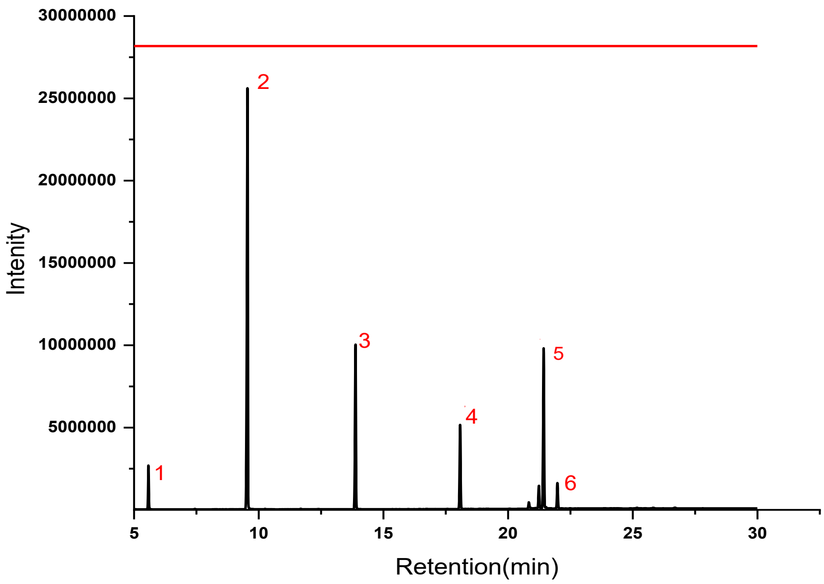


Figure 8. Chromatogram of biodiesel sample using 0.90 g bentonite and 10 mL citronella oil

Table 8. Chemical composition and properties of biodiesel

Peak	Retention (min)	Component	Area % (Relative Abundance)
1	5.7	Citronella Oil	14.3
2	9.4	Methyl Palmitate	44.6
3	13.7	Methyl Laurate	15.7
4	17.9	Geraniol	10.1
5	21.8	Methyl Stearate	12.5
6	23.8	Naphthalene (Bentinite Derived Compound)	2.8

Methyl palmitate is the predominant component, making up 44.6% of the overall relative abundance, according to the quantitative analysis of the chromatographic data. This notable concentration implies that the sample has a high ester content, which is frequently present in biodiesel precursors or particular matrices formed from lipids. This observation is further supported by the presence of Methyl Laurate (15.7%) and Methyl Stearate (12.5%), indicating that a combination of FAME was produced during the synthesis or extraction process.

Because CPO naturally includes substantial proportions of palmitic and oleic acid, these molecules are characteristic FAME constituents of biodiesel made from palm oil. Thus, the successful production of biodiesel from CPO is strongly supported by the predominance of methyl palmitate and methyl oleate in this study.

The distribution of FAME is significant from the standpoint of fuel properties because the ratio of unsaturated to saturated methyl esters has a significant influence on the quality of biodiesel. Saturated FAME molecules like methyl stearate and methyl palmitate typically improve oxidation resistance and CN. Because fuels with higher CNs typically exhibit shorter ignition delays and smoother combustion, this is advantageous for ignition quality. However, by deteriorating cold-flow properties and increasing crystallization tendency, an excessively saturated FAME level may decrease low-temperature operability [25].

The chromatogram of high-quality biodiesel should ideally be dominated by FAME peaks with little interference from catalyst residues, HC fractions, residual glycerides, FFA, residual alcohol, and other non-target substances. Purification is a crucial step in the synthesis of biodiesel, according to recent evaluations, since inadequate purification can lower fuel stability, safety, and engine compatibility even in cases where transesterification yield is acceptable [26].

Both the original oil and components generated by citronella may be present in trace levels, although they do not dominate the chromatographic profile, according to the detection of long-chain alkanes and minor oxygenated compounds. Thus, the fuel's primary composition of FAME species, corresponding to normal biodiesel, is confirmed by the GC–MS results.

3.9 Fourier-transform infrared spectroscopy characterization

Figure 9 displays the biodiesel's FTIR spectrum. The O–H stretching vibrations of the hydroxyl groups are responsible for the wide absorption band seen in the 3200–3500 cm^{-1} range. The inclusion of bentonite and citronella oil causes a discernible shift in this band towards lower wavenumbers, indicating the development of stronger hydrogen bonding networks between biodiesel and the bentonite and citronella oil. All biodiesel samples exhibited the distinctive Si–O stretching vibration of bentonite at about 1030 cm^{-1}, indicating that the bentonite was successfully integrated into the biodiesel. Additionally, the successful loading of citronella oil into the biodiesel is confirmed by the emergence of a distinct peak at around 1730 cm^{-1}, which corresponds to the C=O stretching of citronellal. This peak's strength rose in direct proportion to the oil's concentration, suggesting a dose-dependent assimilation.

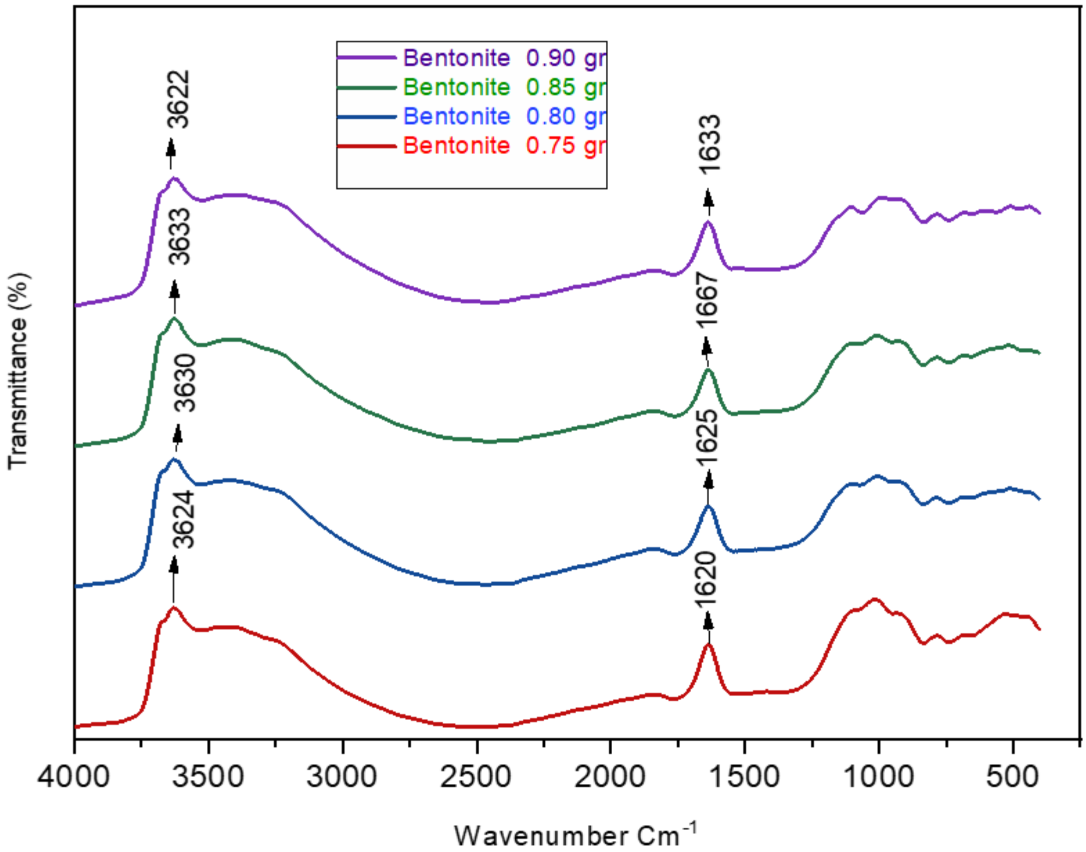


Figure 9. Overlay of the Fourier-transform infrared spectroscopy (FTIR) spectrum of biodiesel samples with variations in bentonite and citronella oil

Absorption bands associated with clay minerals showed bentonite's contribution. Bands about 1630–1640 cm^{-1} are associated with H–O–H bending vibrations of adsorbed water, whereas bands around 3620–3630 cm^{-1} can be attributed to structural Al(Mg)–O–H stretching. Lower-wavenumber bands in the fingerprint region are linked to Al–O–Si and Si–O bending, while bands about 1000–1100 cm^{-1} are associated with Si–O–Si stretching vibrations. These spectral characteristics are characteristic of clay formations based on montmorillonite and bentonite. The involvement of bentonite surface chemistry in adsorption and functional-group interaction has been confirmed by recent Elsevier studies on bentonite-based materials, which also found hydroxyl/water-related characteristics in the high-wavenumber region and Si–O-related bands at about 1030 cm^{-1} [27].

Consistent ester carbonyl peaks were visible in the overlaying FTIR spectra of biodiesel treated with varying bentonite loadings and amounts of citronella oil, suggesting that the basic structure of the biodiesel remained unaltered. Differences in adsorption and residual moisture are reflected in variations in band intensity for hydroxyl and water-related peaks; the C=O wavenumber revealed a strong intensity at about 1740–1784 cm^{-1} [28]. The recorded variations in FFA, viscosity, and flash point are consistent with these observations.

4. CONCLUSIONS

The synthesis, evaluation, characterization, and production of biodiesel from CPO using citronella oil as an oxygenated bio-additive and bentonite as an adsorbent, and the functional assessment of the integrated findings result in the principal conclusions of this work.

About 84% of the biodiesel produced by base-catalyzed transesterification of CPO at a CPO: methanol molar ratio of 1:3 with 2 g NaOH at 65 ℃ for 60 minutes met density, viscosity, and CN requirements but had an inadequate flash point.

Synergistic post-treatment effect: The physicochemical quality of the biodiesel was greatly enhanced by the use of bentonite as a solid adsorbent and citronella oil as an oxygenated bio-additive. This dual strategy improved fuel stability and successfully lowered contaminants like FFA to a range of 0.20–0.87%.

Pareto, ANOVA, and RSM analyses of the processing data revealed that the concentration of citronella oil loading was the main factor influencing both kinematic viscosity and flash point, followed by bentonite concentration. To ensure compliance with SNI 7182-2015 regulations, moderate-to-high doses and higher levels of citronella oil were used to produce optimal fuel quality.

Composition and characterization: GC–MS verified that the improved fuel was mostly composed of FAME, with methyl palmitate and methyl oleate predominating. These compounds match the natural fatty acid composition of CPO.

Structural integrity: FTIR spectroscopy confirmed that triglycerides were successfully converted into biodiesel, showing that the post-treatment procedure successfully modified minor components and physical characteristics without changing the fuel's fundamental molecular structure.

REFERENCES

[1] Liu, Y., Cruz-Morales, P., Zargar, A., et al. (2021). Biofuels for a sustainable future. Cell, 184(6): 1636-1647. https://doi.org/10.1016/j.cell.2021.01.052

[2] Suhara, A., Karyadi, Herawan, S.G., et al. (2024). Biodiesel sustainability: Review of progress and challenges of biodiesel as sustainable biofuel. Clean Technologies, 6(3): 886-906. https://doi.org/10.3390/cleantechnol6030045

[3] Holechek, J.L., Geli, H.M.E., Sawalhah, M.N., Valdez, R. (2022). A global assessment: Can renewable energy replace fossil fuels by 2050? Sustainability, 14(8): 4792. https://doi.org/10.3390/su14084792

[4] Ostojčić, M., Cikoja, M., Flanjak, I., et al. (2024). The influence of qualitative parameters of waste cooking oils and fat on fatty acid methyl esters yield. Chemistry in Industry, 73(11-12): 439-447. https://doi.org/10.15255/kui.2023.062

[5] Simbolon, E., Aisyah, L. (2022). Palm oil biodiesel: Challenges, risks and opportunities for reducing and replacing the non-renewable fossil fuel dependancy - A review. Scientific Contributions Oil and Gas, 36(1): 15-29. https://doi.org/10.29017/scog.36.1.645

[6] Sholihah, A., Murti, S.D.S., Juwita, A.R., Yanti, F.M., Saputra, H. (2019). Characterization of mixed biodiesel and petrodiesel as transportation fuel. International Conference on Sustainable Biomass (ICSB 2019), Bandar Lampung, Indonesia.

[7] Senthil, J., Prabhahar, M., Singh, S., Poudel, R., Achari, V.V.K. (2020). Performance and emission characteristics of citronella oil as an alternative fuel. IOP Conference Series: Materials Science and Engineering, 993: 012026. https://doi.org/10.1088/1757-899X/993/1/012026

[8] Rahimzadeh, H., Tabatabaei, M., Aghbashlo, M., et al. (2018). Potential of acid-activated bentonite and SO3H-functionalized MWCNTs for biodiesel production from residual olive oil under biorefinery scheme. Frontiers in Energy Research, 6: 137. https://doi.org/10.3389/fenrg.2018.00137

[9] Wu, L., Wei, T., Tong, Z., Zou, Y., Lin, Z., Sun, J. (2016). Bentonite-enhanced biodiesel production by NaOH-catalyzed transesterification of soybean oil with methanol. Fuel Processing Technology, 144: 334-340. https://doi.org/10.1016/j.fuproc.2015.12.017

[10] Hasanudin, H., Asri, W.R., Zulaikha, I.S., et al. (2022). Hydrocracking of crude palm oil to a biofuel using zirconium nitride and zirconium phosphide-modified bentonite. RSC Advances, 12(34): 21916-21925. https://doi.org/10.1039/d2ra03941a

[11] Lawan, I., Zhou, W., Idris, A.L., et al. (2020). Synthesis, properties and effects of a multi-functional biodiesel fuel additive. Fuel Processing Technology, 198: 106228. https://doi.org/10.1016/j.fuproc.2019.106228

[12] Salaheldeen, M., Mariod, A.A., Aroua, M.K., Rahman, S.M.A., Soudagar, M.E.M., Fattah, I.M.R. (2021). Current state and perspectives on transesterification of triglycerides for biodiesel production. Catalysts, 11(9): 1121. https://doi.org/10.3390/catal11091121

[13] Fitri, N., Riza, R., Akbari, M.K., Khonitah, N., Fahmi, R.L., Fatimah, I. (2022). Identification of citronella oil fractions as efficient bio-additive for diesel engine fuel. Designs, 6(1): 15. https://doi.org/10.3390/designs6010015

[14] Yahya, S.I., Aghel, B. (2021). Estimation of kinematic viscosity of biodiesel-diesel blends: Comparison among accuracy of intelligent and empirical paradigms. Renewable Energy, 177: 318-326. https://doi.org/10.1016/j.renene.2021.05.092

[15] Chamara, I., Nilmalgoda, H., Wimalasiri, E. (2025). Efficient free fatty acid reduction in palm oil mill effluent (POME) for biodiesel production: Challenges and optimization strategies. Challenges, 16(2): 28. https://doi.org/10.3390/challe16020028

[16] Bemani, A., Xiong, Q., Baghban, A., Habibzadeh, S., Mohammadi, A.H., Doranehgard, M.H. (2020). Modeling of cetane number of biodiesel from fatty acid methyl ester (FAME) information using GA-, PSO-, and HGAPSO- LSSVM models. Renewable Energy, 150: 924-934. https://doi.org/10.1016/j.renene.2019.12.086

[17] Jariah, N.F., Hassan, M.A., Taufiq-Yap, Y.H., Roslan, A.M. (2021). Technological advancement for efficiency enhancement of biodiesel and residual glycerol refining: A mini review. Processes, 9(7): 1198. https://doi.org/10.3390/pr9071198

[18] Alviso, D., Saab, E., Clevenot, P., Romano, S.D. (2020). Flash point, kinematic viscosity and refractive index: Variations and correlations of biodiesel–diesel blends. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(6): 1-15. https://doi.org/10.1007/s40430-020-02428-w
[19] Atabani, A.E., Silitonga, A.S., Badruddin, I.A., Mahlia, T.M.I., Masjuki, H.H., Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renewable and Sustainable Energy Reviews, 16(4): 2070-2093. https://doi.org/10.1016/j.rser.2012.01.003
[20] Naseef, H.H., Tulaimat, R.H. (2025). Transesterification and esterification for biodiesel production: A comprehensive review of catalysts and palm oil feedstocks. Energy Conversion and Management: X, 26: 100931. https://doi.org/10.1016/j.ecmx.2025.100931
[21] Kipkoech, R., Takase, M., Ahogle, A.M.A., Ocholla, G. (2024). Analysis of properties of biodiesel and its development and promotion in Ghana. Heliyon, 10(20): e39078. https://doi.org/10.1016/j.heliyon.2024.e39078
[22] Elgharbawy, A.S., Farghali, M., Osman, A.I., Hanafy, M.A., Al-Muhtaseb, A.H. (2025). Innovative biodiesel production for sustainable energy: Advances in feedstocks, transesterification, and cost efficiency. Biomass and Bioenergy, 201: 108114. https://doi.org/10.1016/j.biombioe.2025.108114
[23] Ramalingam, K., Venkatesan, E.P., Vellaiyan, S., et al. (2023). Substitution of diesel fuel in conventional compression ignition engine with waste biomass-based fuel and its validation using artificial neural networks. Process Safety and Environmental Protection, 177: 1234-1248. https://doi.org/10.1016/j.psep.2023.07.085
[24] Sia, C.B., Kansedo, J., Tan, Y.H., Lee, K.T. (2020). Evaluation on biodiesel cold flow properties, oxidative stability and enhancement strategies: A review. Biocatalysis and Agricultural Biotechnology, 24: 101514. https://doi.org/10.1016/j.bcab.2020.101514
[25] Díez-Valbuena, G., Tuero, A.G., Díez, J., Rodríguez, E., Battez, A.H. (2024). Prediction of the cold flow properties of biodiesel using the FAME distribution and Machine learning techniques. Journal of Molecular Liquids, 400: 124555-124555. https://doi.org/10.1016/j.molliq.2024.124555
[26] Limmun, W., Chungcharoen, T., Rattanamechaiskul, C., Phetpan, K., Limmun, W. (2024). Enhancing biodiesel yield and purification with a recently developed centrifuge machine: A response surface methodology approach. Heliyon, 10(7): e29018. https://doi.org/10.1016/j.heliyon.2024.e29018.
[27] Almahri, A. (2022). The solid-state synthetic performance of bentonite stacked manganese ferrite nanoparticles: Adsorption and photo-fenton degradation of MB dye and antibacterial applications. Journal of Materials Research and Technology, 17: 2935-2949. https://doi.org/10.1016/j.jmrt.2022.02.052
[28] Kurniasih, E., Rahmi, Supardan, M.D., Darusman, Agustina, R., Elfiana, Ridwan, Rahmawati, C.A. (2025). Enzymatic synthesis of sucrose esters from off-grade palm kernel oil methyl ester: Characterization and application as a food emulsifier. International Journal of Design & Nature and Ecodynamics, 20(12): 2729-2743. https://doi.org/10.18280/ijdne.201201