Biodiesel Synthesis: A Green Chemistry Solution for Alternative Energy

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ABSTRACT

This study investigates the synthesis of biodiesel from waste cooking oil using base-catalyzed transesterification with different alcohols: methanol, ethanol, and 2-propanol. The primary objective is to evaluate the biodiesel yield and its physicochemical properties, including pH, color, density, acid value, and water content, under various molar ratios of oil to alcohol. Methanol emerged as the most effective alcohol, with a biodiesel yield of up to 98% achieved. This biodiesel exhibited favorable properties such as a low acid value and an optimal pH, making it suitable for fuel applications. Ethanol and 2-propanol, however, did not perform well under the tested conditions, yielding lower biodiesel amounts and exhibiting suboptimal physicochemical properties. The results emphasize the critical role of the oil-to-alcohol ratio in the production of high-quality biodiesel, with methanol showing superior performance compared to other alcohols. By optimizing this ratio, the study contributes valuable insights into improving biodiesel yield and quality. These findings are significant for the development of sustainable biodiesel production techniques, contributing to global efforts to reduce dependence on fossil fuels and promote renewable energy solutions. By demonstrating the potential of green chemistry, the study advanced sustainable energy solutions through the production of high-quality biodiesel from waste cooking oil. Furthermore, by optimizing the methanol-to-oil ratio and adhering to European standards, the research highlighted how green chemistry can drive innovation toward a more sustainable energy future.

Keywords: biodiesel synthesis; physicochemical properties; renewable energy transesterification; waste cooking oil

INTRODUCTION

The increasing global demand for energy, driven by accelerating population growth and economic expansion, has emerged as a critical concern for the international community. Projections indicate that energy demand will rise by more than 15% by 2050 compared to 2021 levels (Khan et al., 2024). This upward trajectory has been consistent, with an average annual growth rate of approximately 2.1% (Zhang et al., 2022). At present, fossil fuels continue to supply nearly 80% of the world's energy needs, despite their welldocumented environmental consequences. The combustion of these fuels significantly contributes to greenhouse gas (GHG) emissions, including Carbon dioxide (CO_2), methane (CH_4), and black carbon, which intensify global warming and exacerbate the effects of climate change (Moodley & Trois, 2021; Pandey, 2021). The environmental toll of continued fossil fuel reliance underscores the urgent need to transition toward more sustainable energy sources (Ismukurnianto, 2022).

This global issue is particularly pronounced in developing countries such as the Philippines, where GHG emissions are projected to increase from 25 million tons of Carbon dioxide equivalent ($MtCO_2e$) in 2020 to approximately 147 $MtCO_2e$ by 2050 (Bollozos, 2023). This dramatic rise poses significant environmental and social risks, especially in vulnerable regions like General Santos City. Such areas are increasingly susceptible to climate-induced threats, including more intense and frequent natural disasters, sea-level rise, ecosystem disruptions, and negative impacts on public health and livelihoods. These risks highlight the need for robust,

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localized climate mitigation and adaptation strategies aimed at increasing resilience and reducing environmental harm (BIMP-EAGA, 2022).

Within this context, the shift to renewable energy sources has become imperative to reduce dependence on fossil fuels and limit their associated emissions. Among various alternatives, biodiesel has gained attention for its favorable environmental profile. Biodiesel is biodegradable, renewable, and produces significantly fewer emissions compared to petroleum-based diesel (Prabhu et al., 2021). When synthesized under green chemistry principles—which emphasize non-toxic materials, renewable inputs, and energy-efficient processes—biodiesel represents a promising pathway toward cleaner energy production and reduced GHG emissions.

The global relevance of sustainable energy transitions is further emphasized by the United Nations Sustainable Development Goals (SDGs), particularly Goal 7, which seeks to ensure access to affordable, reliable, sustainable, and modern energy, and Goal 13, which calls for urgent action to combat climate change and its impacts. Goal 13 aims to enhance resilience to climate hazards, integrate climate strategies into policy frameworks, and strengthen institutional capacities for mitigation and adaptation. Goal 7 emphasizes increasing the share of renewable energy and improving energy efficiency worldwide. Together, these goals highlight the importance of reducing fossil fuel reliance and transitioning to renewable energy to achieve a sustainable and resilient future.

Although numerous studies have examined the production of biodiesel from diverse raw materials, including kaolin and eggshell catalysts (Giwa, 2021), vegetable oils (Kondrasheva, 2023), and *Ricinus communis L.* seed oil using Calcium oxide nanoparticles (Jain, 2022), much of the existing literature focuses on yield optimization and feedstock characteristics (Bôas, 2022). There remains a notable research gap in the application of green chemistry to biodiesel synthesis, particularly in terms of utilizing waste feedstocks, enhancing catalyst reusability, and minimizing environmental impact through process optimization.

This study aims to address that gap by systematically investigating the synthesis of biodiesel through green chemistry approaches. Specifically, the research focuses on the use of waste cooking oil and environmentally friendly catalysts to produce biodiesel, assessing both the environmental implications and sustainability of the process. By doing so, this study contributes to the development of alternative energy solutions that align with global sustainability targets and promote environmental stewardship.

2. Objectives

This study aimed to provide a green chemistry-based solution for sustainable alternative energy production through the synthesis of biodiesel from waste cooking oil.

Specifically, the research sought to address the following objectives:

1. To determine the percentage yield of biodiesel produced using various molar ratios of alcohol (ROH) to waste cooking oil (RCOOR), including methanol, ethanol, and 2-propanol.
2. To evaluate the physicochemical properties of the biodiesel produced using different types of alcohols (methanol, ethanol, and 2-propanol), specifically pH, color, density, acid number and water content.
3. To determine whether there is a statistically significant difference in the physicochemical properties among methanol-based, ethanol-based, and 2-propanol-based biodiesel samples.
4. To compare the properties of locally synthesized biodiesel with those of biodiesel conforming to the European Standard (EN 14214).

MATERIALS AND METHODS

This study employed an experimental research design to synthesize biodiesel from waste cooking oil using green chemistry principles. The research compared the effects of three alcohols—methanol, ethanol, and 2-propanol—at varying molar ratios on biodiesel yield and physicochemical properties. A comparative analysis was conducted between the properties of locally produced biodiesel and the European Standard for biodiesel (EN 14214).

The materials used in this study included waste cooking oil (RCOOR), which was used as the feedstock for biodiesel synthesis. The waste cooking oil was sourced from local providers and was filtered to remove any particulate matter prior to use. Three different alcohols were employed for the transesterification process: methanol (CH_3OH), ethanol (C_2H_5OH), and 2-propanol (C_3H_7OH). Sodium hydroxide (NaOH) served as the base catalyst for the transesterification reaction. The catalyst was prepared by dissolving NaOH in methanol at a concentration of 1% (w/v). In addition, standard biodiesel (EN 14214), which complies with the European biodiesel standards, was used as a reference for comparison.

Various apparatus and equipment were utilized throughout the experimental procedure. Glassware including conical flasks, graduated cylinders, beakers, and burettes were used for preparing the reactants, measuring liquids, and conducting titrations. A heating mantle was employed to maintain a constant temperature during the transesterification process, while a magnetic stirrer was used to ensure the thorough mixing of the reactants. After the reaction, a separation funnel was used to separate the biodiesel from the glycerol. To measure the density of the biodiesel samples, a refractometer was used, and a pH meter was employed to determine the pH of the biodiesel. The color of the biodiesel was evaluated using a colorimeter, while a titration setup was used to determine the acid number. Finally, the water content in the biodiesel was measured using a Karl Fischer titrator, a specialized instrument for precise water content analysis.

Biodiesel was synthesized using the base-catalyzed transesterification method, where waste cooking oil (RCOOR) was reacted with different alcohols (methanol, ethanol, and 2-propanol) in the presence of Sodium hydroxide (NaOH) as a catalyst. For the preparation, a 1% (w/v) NaOH solution was first prepared by dissolving NaOH in methanol (for methanol trials), ethanol (for ethanol trials), and 2-propanol (for 2-propanol trials). The catalyst solution was then added to the corresponding alcohol, and the mixture was stirred until homogeneous. In the transesterification reaction, 100 mL of waste cooking oil was measured into a 500 mL conical flask, and the alcohol-catalyst mixture was added according to specific molar ratios. The reaction mixture was then heated to 60 °C and continuously stirred for 1.5 hours to allow the transesterification reaction to occur. After the reaction, the mixture was cooled to room temperature.

For the separation of the biodiesel, the reaction mixture was transferred to a separation funnel and allowed to settle for 24 hours. The biodiesel layer (methyl/ethyl/propyl ester) was separated from the glycerol byproducts and collected for further analysis. The biodiesel was then washed with warm distilled water several times to remove residual catalyst and impurities. Finally, the purified biodiesel was dried in a vacuum oven at 50°C for 2 hours to remove excess water.

The physicochemical properties of the biodiesel were evaluated to assess its suitability as an alternative fuel. The properties measured included pH, color, density, acid number, and water content. The pH of the biodiesel was measured using a calibrated pH meter. The color was observed and compared visually using a standardized color scale (ASTM D1500). The density was determined using a refractometer as per ASTM D4052. The acid number was determined by titration with a standardized Potassium hydroxide (KOH) solution, following ASTM D664. The water content was measured using the Karl Fischer titration method, according to ASTM E203.

To assess the statistical significance of differences in the physicochemical properties among the biodiesel samples produced with methanol, ethanol, and 2-propanol, a one-way analysis of variance (ANOVA) was conducted. A p-value of less than 0.05 was considered statistically significant.

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Finally, the properties of the locally synthesized biodiesel were compared to the European Standard for biodiesel (EN 14214) in terms of pH, color, density, acid value, and water content. This comparison provided insight into the compliance of the locally synthesized biodiesel with international quality standards.

RESULTS

This section presents the data on the percentage yield of biodiesel, derived from varying molar ratios of alcohol (ROH) to waste cooking oil (RCOOR). It also includes the examination of physicochemical properties of the biodiesel produced using different types of alcohol—methanol, ethanol, and 2-propanol— including pH, color, density, acid number, and water content. The results provided a comprehensive comparison of how these factors influenced the quality and yield of biodiesel.

Table 1 presents experimental data on the yield of biodiesel using different types of alcohol and molar ratios of waste cooking oil to alcohol. The types of alcohol tested include methanol (CH_3OH), ethanol (C_2H_5OH), and 2-propanol (C_3H_7OH). Also shown in the table are different molar ratios of waste cooking oil to alcohol (10:30, 5:3, and 5:9), with each experiment replicated three times to record the mass in grams and the percentage yield.

For methanol at a 10:30 ratio, the replicates (R1, R2, R3) produced masses of 82.311 g, 82.317 g, and 81.945 g, respectively, with a consistent percentage yield of 82%. The mean yield, while not explicitly stated, would be approximately 82 %. At a 5:3 ratio, the replicates produced masses of 88.093 g, 89.000 g, and 87.985 g, corresponding to percentage yields of 88 %, 89 %, and 88 %. The mean yield for this ratio is around 88.4 %.

Table 1 Percentage Yield of Biodiesel from varying Molar Ratios of Alcohol (ROH) to Waste Cooking Oil (RCOOR)

Types of alcohol	Waste cooking oil to alcohol ratio	Replicate	Mass (g)	Percentage yield
		R1	82.311	82
	10:30	R2	82.317	82
		R3	81.945	82
		Mean	82.191	82
		R1	88.093	88
Methanol, CH_3OH	5:3	R2	89.000	89
		R3	87.985	88
		Mean	88.359	88.33
		R1	98.594	98
	5:9	R2	97.844	98
		R3	96.678	97
		Mean	97.705	97.67
Ethanol, C_2H_5OH	*		**	**
2-Propanol, C_5H_7OH	*		**	**

Note: * Same ratio with methanol

** Negative results

For the 5:9 ratio, the replicates produced masses of 98.594 g, 97.844 g, and 96.678 g, with percentage yields of 98 %, 98 %, and 97 %. The mean yield was approximately 97.7 %.

In contrast, both ethanol and 2-propanol did not produce positive results under the conditions tested. The table notes "negative results" with an asterisk explanation indicating that the same ratio used with methanol did not yield biodiesel with these alcohols.

Table 2 summarizes the outcomes of experiments using different alcohols and waste cooking oil ratios to produce biodiesel, with a focus on the color of the resulting product. The table was divided based on the types of alcohol used: methanol (CH_3OH), ethanol (C_2H_5OH), and 2- propanol (C_3H_7OH).

Table 2 The Physicochemical Property of Biodiesel Produced in Terms of colour

Types of alcohol	Waste cooking oil to alcohol ratio	Replicate	Colour
		R1	Yellow
	10:30	R2	Yellow
		R3	Yellow
		R1	Yellow
Methanol, CH_3OH	5:3	R2	Yellow
		R3	Yellow
		R1	Amber
	5:9	R2	Amber
		R3	Amber
Ethanol, C_2H_5OH	*		**
2-Propanol, C_5H_7OH	*		**

Note: * Same ratio with methanol

**Negative results

For methanol, three different waste cooking oil to alcohol ratios were tested: 10:30, 5:3,

and 5:9. In the first two ratios (10:30 and 5:3), all replicates (R1, R2, R3)

resulted in yellow- colored biodiesel. The mean color for these ratios also remained yellow. However, for the 5:9 ratio, the color of the biodiesel changed to amber for all replicates, with the mean color also recorded as amber.

For ethanol and 2-propanol, the table indicated that the same ratios as methanol were tested (*). However, the results were negative (**), implying that these alcohols did not produce biodiesel successfully or did not produce a usable product under the tested conditions.

Table 3 presents data on the pH levels of biodiesel produced using different types of alcohols and waste cooking oil ratios. This table focuses on how the pH of the resulting biodiesel varies with the type of alcohol and the ratio of waste cooking oil to alcohol.

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Table 3 The Physicochemical Property of Biodiesel Produced in Terms of pH

Types of Alcohol	Waste Cooking Oil to Alcohol Ratio	Replicate	pH
		R1	7.3
	10:30	R2	7.3
		R3	7.2
		R1	7.6
Methanol, CH_3OH	5:3	R2	7.4
		R3	7.4
		R1	8.6
	5:9	R2	8.4
		R3	8.6
Ethanol, C_2H_5OH	*		**
2-Propanol, C_5H_7OH	*		**

Note: *Same ratio with methanol

**Negative results

For methanol (CH_3OH), three waste cooking oil to alcohol ratios were tested: 10:30, 5:3, and 5:9. The pH values for the 10:30 ratio showed slight consistency, with replicates R1 and R2 having a pH of 7.3 and R3 as lightly lower pH of 7.2. The 5:3 ratio showed a higher pH level with R1 at 7.6 and R2 and R3 at 7.4. The highest pH levels were observed in the 5:9 ratio, where R1 and R3 had a pH of 8.6 and R2 a pH of 8.4. These results indicated that increasing the ratio of alcohol tended to increase the pH of the resulting biodiesel when methanol was used.

Table 4 shows the density of biodiesel produced using different types of alcohols and various waste cooking oil to alcohol ratios. This data was crucial because the density of biodiesel is a key factor in determining its suitability as a fuel.

Table 4 The Physicochemical Property of Biodiesel Produced in Terms of Density

Types of Alcohol	Waste Cooking Oil to Alcohol Ratio	Replicate	Density (kg/m^3) at 20°C
		R1	872.021
	10:30	R2	869.102
		R3	870.981
		R1	884.314
Methanol, CH_3OH	5:3	R2	887.306
		R3	885.070
		R1	894.472
	5:9	R2	892.092
		R3	895.721
Ethanol, C_2H_5OH	*		**
2-Propanol, C_5H_7OH	*		**

Note: *Same ratio with methanol

**Negative results

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For methanol (CH_3OH), three waste cooking oil to alcohol ratios were tested: 10:30, 5:3, and 5:9. The densities for the 10:30 ratio ranged slightly, with R1 at 872.021 kg/m³, R2 at 869.102 kg/m³, and R3 at 870.981 kg/m³. For the 5:3 ratio, the densities were slightly higher, with R1at 884.314 kg/m³, R2 at 887.306 kg/m³, and R3 at 885.070 kg/m³. The highest densities were observed in the 5:9 ratio with R1 at 894.472 kg/m³, R2 at 892.092 kg/m³, and R3 at 895.721 kg/m³.

Table 5 provides data on the acid values of biodiesel produced using different alcohols and waste cooking oil to alcohol ratios. Acid value is a critical parameter indicating the amount of free fatty acids in the biodiesel,

which affects its quality and stability.

Table 5 The Physicochemical Property of Biodiesel Produced in Terms of Acid Value

Types of Alcohol	Waste Cooking Oil to Alcohol Ratio	Replicate	Acid Value (mg KOH/g)
		R1	0.4
	10:30	R2	0.5
		R3	0.4
		R1	0.3
Methanol, CH_3OH	5:3	R2	0.3
		R3	0.4
		R1	0.3
	5:9	R2	0.2
		R3	0.2
Ethanol, C_2H_5OH	*		**
2-Propanol, C_5H_7OH	*		**

Note: *Same ratio with methanol

**Negative results

For methanol (CH_3OH), three waste cooking oil to alcohol ratios were tested: 10:30, 5:3, and 5:9. At the 10:30 ratio, the acid values for the three replicates (R1, R2,

R3) are 0.4 mg KOH/g, 0.5 mg KOH/g, and 0.4 mg KOH/g, respectively. These values were slightly higher but still within acceptable limits. For the 5:3 ratio, the acid values are 0.3 mg KOH/g for R1 and R2, and 0.4 mg KOH/g for R3, showing a slight improvement compared to the 10:30 ratio. At the 5:9 ratio, the acid values further decreased, with R1 at 0.3 mg KOH/g and both R2 and R3 at 0.2 mg KOH/g, indicating better quality biodiesel with lower fatty.

For ethanol (C_2H_5OH) and 2-propanol (C_3H_7OH), the table indicated that the same ratios as methanol were tested (*), but both alcohols resulted in negative outcomes (**). This implied that these alcohols did not produce biodiesel with acceptable acid values under the tested conditions.

Table 6 provides data on the water content in biodiesel produced using different types of alcohols and various waste cooking oil to alcohol ratios. Water content was critical parameter in biodiesel quality, as excessive water could lead to issues in fuel performance and storage stability.

For methanol (CH_3OH), three waste cooking oil to alcohol ratios were tested: 10:30, 5:3, and 5:9. The water content for the10:30 ratio showed some variation among the replicates, with R1 having a water content of 320 mg/kg, R2 at 346 mg/kg, and R3 at 337 mg/kg. For the 5:3 ratio, the water content was slightly higher, with R1 at 394 mg/kg, R2 at 380 mg/kg, and R3 at 437 mg/kg. The highest water content was observed in the 5:9 ratio, where R1 has 473 mg/kg, R2 has 491 mg/kg,

Table 6 The Physicochemical Property of Biodiesel Produced in Terms of Water Content

Types of Alcohol	Waste Cooking Oil to Alcohol Ratio	Replicate	Water Content (mg/Kg)
		R1	320
	10:30	R2	346
		R3	337
		R1	394
Methanol, CH_3OH	5:3	R2	380
		R3	437
		R1	473
	5:9	R2	491
		R3	477
Ethanol, C_2H_5OH	*		**
2-Propanol, C_5H_7OH	*		**

Note*:* *Same ratio with methanol

**Negative results

and R3 has 477 mg/kg. These results indicated that increasing the alcohol ratio led to an increase in the water content of the biodiesel produced with methanol.

For ethanol (C_2H_5OH) and 2-propanol (C_3H_7OH), the table noted that the same ratios as methanol were tested (*), but both alcohols resulted in negative outcomes (**). This indicates that these alcohols did not produce biodiesel successfully or resulted in products with undesirable properties under the tested conditions. This aligned with the previous findings where methanol was the only alcohol to produce consistent and measurable biodiesel properties.

The next section presents whether there were significant differences between the physicochemical properties of methanol biodiesel across three ratios of waste cooking oil to alcohol. This analysis helped determine the most suitable ratio for biodiesel production based on the measurable outcomes observed in the previous experiments. By comparing these properties, the researcher identified which ratio offered the best performance in terms of biodiesel quality and consistency.

The succeeding tables presents the results of analysis of variance (ANOVA) to test the significance of difference in means between waste cooking oil to alcohol ratios. For post-hoc test results, see Appendix A.

Table 7 summarizes the results of an ANOVA test, assessing differences in biodiesel yields across various oil-to-alcohol ratios. The between-groups variation, indicating differences due to the ratios, had a sum of squares (SS) of 372.667 with 2 degrees of freedom *(df)*, and a mean square (MS) of 186.333. The Fvalue of 838.5, which significantly exceeded the critical F-value (F crit) of 5.143, and a P-value of less than .001, confirmed that the yield differences are highly significant (Field, 2021; Frost, 2021).

Table 7 Analysis of Variance in Percentage Yield Between Waste Cooking Oil to Alcohol Ratios

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	372.667	2	186.333	838.5	<.001	5.143
Within Groups	1.333	6	0.222			
Total	374	8				

Within-groups variation, showing variability within each group, had an SS of 1.333 with 6 *df* and an MS of 0.222. The low within-groups variability compared to the between-groups highlighted the substantial impact of different ratios on biodiesel yield. The total SS is 374 with 8 *df*, reinforcing that the ratios of waste cooking oil to alcohol significantly affected biodiesel yield.

The total variation, combining both between-groups and within-groups variations, sums up to 374, with a total of 8 degrees of freedom. The significant F-value and low P-value implied that the ratios of waste cooking oil to alcohol had a profound impact on the percentage yield of biodiesel. This finding underscored the necessity of optimizing the oil-to-alcohol ratio to enhance biodiesel yield efficiency.

Table 8 presents an ANOVA summary that evaluated the variability in pH levels across different ratios of waste cooking oil to alcohol. The analysis showed a significant effect of the different ratios on pH, indicated by an F-value of 139.111, which significantly exceeded the critical F-value (F crit) of 5.143. With a P-value of less than .001, the results affirmed statistically significant differences between the groups.

Table 8 Analysis of Variance in pH Between Waste Cooking Oil to Alcohol Ratios

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.782	2	1.391	139.111	<.001	5.143
Within Groups	0.06	6	0.01			
Total	2.842	8				

The table details a between-groups sum of squares (SS) of 2.782 with 2 degrees of freedom *(df)*, yielding a mean square (MS) of 1.391, which represented the average variance among the different ratios. The within-groups SS was notably smaller at 0.06 with 6 *df*, resulting in an MS of 0.01, indicating minimal variability within individual groups of ratios. This low within-group variance reinforced the consistency of pH measurements within each ratio group.

Table 9 presents the ANOVA results that evaluated the variability in biodiesel density across different waste cooking oil to alcohol ratios. The table reveals a significant effect of these ratios on biodiesel density, evidenced by an F-value of 157.510, which substantially exceeded the critical F-value (F crit) of 5.143, and a P-value of less than. 001. These results confirmed statistically significant differences in density between the tested groups.

Table 9 Analysis of Variance in Density Between Waste Cooking Oil to Alcohol Ratios

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	840.932	2	420.466	157.510	<.001	5.143

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Within Groups	16.017	6	2.69			
Total	856.949	8				

The between-groups sum of squares (SS) is 840.932 with 2 degrees of freedom *(df)*, resulting in a mean square (MS) of 420.466. This high MS indicated considerable variability in density due to the different ratios. In contrast, the within-groups SS was 16.017 with 6 *df*, yielding an MS of 2.669, which highlighted minimal variability within each ratio group. The clear difference between the between-groups and withingroups variances underscored the substantial impact of the oil-to-alcohol ratio on biodiesel density.

Table 10 presents the ANOVA results evaluating the differences in acid values of biodiesel produced using various waste cooking oil to alcohol ratios. The table revealed significant differences in acid values among the different ratios, as indicated by an F-value of 9, which exceeded the critical F-value (F crit) of 5.143, and a P-value of 0.016, suggesting statistical significance.

Table 10 Analysis of Variance in Acid Value Between Waste Cooking Oil to Alcohol Ratios

Source of Variation	SS	df	MS	F	P-Value	F cri
Between Groups	0.060	2	0.030	9	0.016	5.143
Within Groups	0.020	6	0.003			
Total	0.08	8				

The between-groups sum of squares (SS) was 0.060 with 2 degrees of freedom *(df)*, resulting in a mean square (MS) of 0.030. This indicated that the variance due to different ratios is substantial. In contrast, the within-groups SS was 0.020 with 6 *df*, yielding an MS of 0.003, showed minimal variability within each group. The total SS of 0.080 with 8 *df* further confirmed the findings.

Table 11 presents the ANOVA results evaluating the differences in water content of biodiesel produced using various ratios of waste cooking oil to alcohol. The table showed a significant difference in water content among the different ratios, evidenced by an F-value of 41.886, which was well above the critical F-value (F crit) of 5.143, and a P-value of <.001, indicating statistical significance.

The between-groups sum of squares (SS) was 32000.888 with 2 degrees of freedom *(df)*, resulting in a mean square (MS) of 16000.444. This high MS indicated considerable variability in water content attributable to the different ratios. In contrast, the within-groups SS was 2292.000 with 6 *df*, yielding an MS of 382.000, which suggested lower variability within each group. The total SS was 34292.888 with 8 *df*.

Table 11 Analysis of Variance in Water Content Between Waste Cooking Oil to Alcohol Ratios

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	32000.88	2	16000.44	41.886	<.001	5.143
Within Groups	2292.00	6	382.00			
Total	34292.88	8				

Table 12 shows the comparison of the properties of synthesized biodiesel with the European standards for biodiesel quality. The properties analyzed include pH, color, density, acid value, and water content, which were critical for determining the fuel's suitability and performance.

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Table 12 Comparison of Physicochemical Properties Between the Biodiesel of the Present Study and the European Standard (EN14214)

Properties	Synthesized Biodiesel	European Standard (EN14214)
pH	7.756	Around pH 7 (neutral)
Color	Yellow	Golden yellow to amber, clear and uniform
Density at 15°C(kg/m³)	883.453	860-900
Acid Value (mg KOH/g)	0.333	Maximum 0.5
Water Content (mg/kg)	406.111	Maximum 500

The pH of the synthesized biodiesel was 7.756, slightly above the neutral pH of around 7, as specified by the European Standard. This indicated that the biodiesel was almost neutral, which was desirable as it suggested stability and minimal corrosiveness, aligning closely with the standard requirements (European Standard, EN14214).

The color of the synthesized biodiesel was yellow, which matched the European standard description of biodiesel being a golden yellow to amber color, clear and uniform. This uniform color was an indicator of good quality and proper processing, ensuring that the fuel was free from impurities and suitable for use (European Standard, EN14214).

The density of the synthesized biodiesel at 15°C was 883.453 kg/m³, falling within the European standard range of 860-900 kg/m³. This conformity indicated that the biodiesel had the appropriate mass per unit volume, which was crucial for engine performance and efficiency (European Standard, EN14214).

The acid value of the synthesized biodiesel was 0.333 mg KOH/g, well below the maximum allowable limit of 0.5 mg KOH/g set by the European standard. A low acid value was essential for the longevity of the engine and fuel system, as it indicated low levels of free fatty acids and reduced the risk of corrosion and deposits (European Standard, EN14214). The water content of the synthesized biodiesel was 406.111 mg/kg, which was within the European standard maximum of 500 mg/kg. Properly controlled water content was crucial to prevent microbial growth and avoid issues such as fuel system corrosion and reduced combustion efficiency (European Standard, EN14214).

DISCUSSION

This part of the study interprets the results related to the biodiesel production process, with a focus on the effects of varying alcohol-to-oil ratios and different alcohol types on biodiesel yield and quality. It explores the analysis of key physicochemical properties such as pH, color, density, acid number, and water content, and how these factors influence the overall performance of the biodiesel. By comparing the performance of methanol, ethanol, and 2-propanol as alcohols in the transesterification process, this section aims to provide insights into their roles in optimizing biodiesel production for improved efficiency and quality.

For the data on the yield of biodiesel using different types of alcohol and molar ratios of waste cooking oil to alcohol, Table 1 suggests that methanol was most effective alcohol for producing biodiesel from waste cooking oil under the tested conditions, with higher methanol ratios (5:9) showing the highest yields, around 98 %. ethanol and 2-propanol, however, may have required different conditions to be effective or were inherently less effective in this process.

Several recent studies highlighted the importance of methanol in biodiesel production. A study of Ulukardesler (2023) emphasized that the molar ratio of methanol to oil plays acritical role in achieving high biodiesel yields. Specifically, increasing the methanol to oil ratio can significantly enhance the conversion efficiency, with yields increasing from 70 % to 95 % as the ratio is raised from 9:1 to 15:1, using KOH as a catalyst. This aligned with the results in Table1, where varying the methanol ratio directly impacted the yield.

Moreover, the study of Devaraj et al. (2020) confirmed these findings, indicating that methanol is highly effective in biodiesel production from waste cooking oil, particularly when the correct molar ratios and catalysts are used. This study also noted that while other alcohols like ethanol and 2-propanol can be used, they often result in lower yields or negative results under similar conditions. Farouk (2024) proved that the use of ethanol and 2-propanol was less effective due to its lower reactivity compared to methanol. The different molecular structures and properties of these alcohols affect the reaction kinetics, often leading to lower yields and biodiesel with less desirable physical and chemical properties.

Table 2 presents the results of experiments using different types of alcohol and varying molar ratios of waste cooking oil to alcohol, with a particular focus on the color of the resulting biodiesel. It highlights that methanol was the only alcohol among the three that produced biodiesel with a consistent color outcome, varying between yellow and amber depending on the specific oil to alcohol ratio used. The other two alcohols, ethanol and 2-propanol, failed to produce biodiesel under the tested conditions.

Methanol proved to be highly effective for biodiesel production from waste cooking oil, particularly at specific ratios. Using methanol-to-oil ratios ranging from 3:1 to 9:1 generally increased biodiesel yield, though higher ratios may decrease yield due to methanol's emulsifying properties, which could potentially affect the color of the biodiesel. This aligned with findings of Tsaoulidis et al. (2023) and Velmurugan et al. (2022) which showed that methanol at different ratios could produce varying biodiesel colors, such as yellow and amber.

Overall, the inefficiency of these alcohols under tested conditions suggested less favorable outcomes, including potential color inconsistencies. These insights supported further research focused on optimizing methanol-based biodiesel production while exploring alternative conditions for ethanol and 2propanol.

Table 3 presents the pH levels of biodiesel produced using different types of alcohols and waste cooking oil ratios. Velmurugan and Warrier (2022) highlighted that higher methanol concentrations in the transesterification process can lead to higher pH values, as seen in the production of biodiesel from waste cooking oil. The increase in the alcohol ratio not only improves yield but also influenced the properties of the biodiesel, including pH. This aligned with the observation of increased pH levels at higher alcohol ratios.

Also, Neupane (2022) emphasized that increasing the alcohol-to-oil ratio enhanced the biodiesel yield and conversion efficiency. For instance, a ratio of 6:1 (alcohol to oil) resulted in a 99 % conversion rate, demonstrating that higher alcohol ratios positively affect the reaction's efficiency and potentially the pH of the resulting biodiesel.

For ethanol (C_2H_5OH) and 2-propanol (C_3H_7OH), the table noted that the same ratios as methanol were tested (*). However, both alcohols resulted in negative outcomes (**), indicating they did not produce biodiesel or produced biodiesel with undesirable properties under the tested conditions. This suggests that methanol was more effective in producing biodiesel with measurable pH properties compared to ethanol and 2-propanol.

The data presented in Table 3, along with the previous one on color, emphasized that methanol was the most suitable alcohol among the three tested for biodiesel production. The variations in pH with different ratios of waste cooking oil to methanol also provided insights into optimizing the production process for desired pH levels in biodiesel. These findings guided further research and industrial applications in biodiesel production, focusing on the use of methanol and appropriate oil-to-alcohol ratios.

Table 4 shows the density of biodiesel produced using different types of alcohol and various waste cooking oil-to-alcohol ratios. The results indicate a trend where increasing the alcohol ratio led to a higher density in the biodiesel produced with methanol.

Studies of Ennetta (2022) and Mittal et al. (2022) showed that biodiesel produced with higher methanol ratios tended to have increased density due to the formation of more methyl esters. Increasing the alcohol ratio also affected the density of the biodiesel, with higher ratios leading to an increase in density because of the formation of more ester compounds and the complete conversion of triglycerides into biodiesel.

For ethanol (C_2H_5OH) and 2-propanol (C_3H_7OH), the table indicated that the same ratios as methanol were tested (*), but both alcohols resulted in negative outcomes (**), meaning they did not produce biodiesel successfully or resulted in unusable products under the tested conditions. This again highlighted methanol's superiority in the biodiesel production process in terms of yielding measurable and usable outcomes.

The findings from Table 4, combined with those from the previous tables on color and pH, provides a comprehensive overview of the physicochemical properties of biodiesel produced using methanol. The data indicated that methanol not only consistently produces biodiesel but also allowed for control over the density of the product by adjusting the oil to alcohol ratio. This information is valuable for optimizing biodiesel production processes to meet specific fuel standards and performance requirement.

Data from Table 5 highlights that methanol is the most effective alcohol for producing biodiesel with acceptable acid values across different waste cooking oil to alcohol ratios. Lower acid values, particularly observed at the 5:9 ratio, suggest that this ratio is optimal for producing higher quality biodiesel with reduced free fatty acid content. This is crucial for ensuring the fuel's stability and reducing the risk of engine corrosion and deposits.

In this study, the acid values decreased with an increasing alcohol ratio, indicating improved biodiesel quality. This trend aligned the study of Tayeb (2024), which showed that higher methanol ratios in the transesterification process tended to reduce the acid value of biodiesel. Lower acid values corresponded to lower free fatty acid content, which is essential for high-quality biodiesel production.

Studies have shown that higher methanol ratios during the transesterification process reduced the acid value of the produced biodiesel, resulting in lower free fatty acid content and improved biodiesel quality. Nabgan (2022) and Ahmed (2022) highlighted that optimizing the methanol to oil ratio is critical for achieving high-quality biodiesel with low acid values, which are essential for reducing corrosive effects and improving the fuel's overall performance and stability.

Data about methanol proved to be a superior alcohol for biodiesel production, yielding biodiesel with desirable acid values across various ratios, while ethanol and 2-propanol failed to produce suitable results. Optimizing the waste cooking oil to methanol ratio, especially favoring the 5:9 ratio, can significantly improve biodiesel quality by minimizing acid content.

Moreover, results has shown that the water content in biodiesel could increase with a higher methanol to oil ratio due to the hygroscopic nature of methanol, which absorbs water from the environment. Studies of Sahani et al. (2020) and Ishak and Kamari (2019) aligned with the observation that higher methanol content could introduce more water into the biodiesel. Biodiesel production using used cooking oil and mixed metal oxide catalysts noted that the optimal methanol-to-oil ratio for their process led to significant biodiesel yield, but also increased the water contents lightly as the methanol ratio increased.

Additionally, recent advances in transesterification processes highlighted the importance of controlling water content during biodiesel production, as excessive water could lead to soap formation and decrease the overall quality of biodiesel. Thus, while a higher methanol ratio could improve the conversion process and yield, it also necessitated careful management of water content to maintain fuel quality (Farouk, 2024).

Data on water content, in conjunction with the previous tables on color, pH, and density, showed the importance of methanol in biodiesel production. Methanol consistently produced biodiesel with measurable properties, although the water content tended to increase with higher oil to alcohol ratios. This information was crucial for optimizing biodiesel production processes, as controlling water content was essential for ensuring fuel quality and performance. By understanding the relationship between the alcohol type, the oil to alcohol ratio, and the resulting biodiesel properties, producers could fine-tune their processes to achieve the desired fuel characteristics. Having thoroughly examined the physicochemical properties of biodiesel produced using different alcohols—methanol, ethanol, and 2-propanol—across various parameters such as color, pH, density, and water content, we shifted our focus to a comparative analysis.

Table 7 presents the differences in biodiesel yields across various oil-to-alcohol ratios, highlighting the importance of optimizing this ratio to maximize biodiesel yield efficiency. A study by Vishal et al. (2020) highlighted that optimizing the ratio is crucial for maximizing biodiesel yield, emphasizing the role of alcohol in the transesterification process. Similarly, Dwivedi (2022) confirmed that adjusting the oil-toalcohol ratio significantly affected the yield, supporting the need for precise optimization to enhance biodiesel production efficiency.

These results were essential for biodiesel production, emphasizing the need for careful selection of the oil-to-alcohol ratio. The significant differences highlighted by the ANOVA test in optimizing the oil-toalcohol ratio for biodiesel production were crucial for enhancing yield and efficiency. Study of Zahed (2022) showed that optimizing the oil-to-alcohol ratio can significantly impact biodiesel yield, leading to more efficient and cost-effective production processes. The study highlighted the importance of optimizing production parameters for maximizing yield and efficiency. Similarly, research by Chiedu (2024) emphasized the necessity of careful selection and optimization of production variables to enhance biodiesel quality and yield.

To assess the variability in pH levels across different waste cooking oil-to-alcohol ratios, Table 8 shows a substantial variance between groups compared to within groups, emphasizing the significant influence that different waste cooking oil-to-alcohol ratios have on the pH of biodiesel. This suggests that modifying these ratios can markedly affect the chemical properties of the resulting biodiesel. These findings are crucial for optimizing biodiesel formulations to enhance both its quality and performance.

A study by Kamran et al. (2020) supported the notion that optimal ratios were important for improving biodiesel properties. The study discussed the effects of various transesterification parameters, including the oil-to-alcohol ratio, on biodiesel properties. The research highlighted that adjusting the methanol ratio significantly influenced the pH and overall quality of biodiesel. Also, Borah et al. (2020) highlighted that the methanol to oil ratio played a critical role in determining the pH and other characteristics of biodiesel produced from waste cooking oil. Their findings underscored the need to finetune these ratios to achieve the desired chemical properties and enhance biodiesel performance.

These statistical insights emphasized the critical role of precise ratio configurations in achieving desired biodiesel properties, facilitating targeted improvements in biodiesel production processes.

Table 9 presents a marked difference between the variance among groups and the variance within groups, indicating that the oil-to-alcohol ratio significantly influences the density of the biodiesel.

Recent studies highlighted the significant impact of the oil-to-alcohol ratio on the density of biodiesel. The variability in density observed due to different ratios underscored the importance of optimizing these ratios for biodiesel production. For instance, a study by Jain et al. (2022) emphasized the optimization of alkali-catalyzed transesterification of rubber oil, which significantly affected the density of the produced biodiesel, demonstrating the crucial role of alcohol ratio in determining biodiesel properties.

Also, Khan in 2023 investigated the transesterification conditions of rapeseed and sunflower oil, revealing that the type and concentration of alcohol used could significantly influence the density and overall quality of

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biodiesel. This study supported the notion that adjusting the alcohol ratio was pivotal in achieving optimal biodiesel characteristics.

It further consolidated the findings, suggesting that optimizing the oil-to-alcohol ratio is crucial for achieving desired biodiesel density. Such insights were vital for refining biodiesel production processes to improve fuel quality and efficiency. These statistical analyses underscored the importance of precise ratio configurations in biodiesel production, which could lead to significant improvements in fuel properties and performance.

Results showed in Table 10 demonstrates the critical impact of the oil-to-alcohol ratio on the acid value of biodiesel, highlighting the need for precise optimization of these ratios to produce high-quality biodiesel with desirable acid values. The significant between-group variance relative to within- group variance suggested that adjusting the ratios could effectively control the acid value, which was vital for biodiesel stability and performance.

Studies had shown that adjusting these ratios could effectively control the acid value, which was crucial for biodiesel stability and performance. For instance, research by Dwivedi et al. (2020) demonstrated that optimizing the alcohol-to-oil ratio significantly influenced biodiesel properties, including acid value, thereby enhancing fuel quality and engine performance. Additionally, Chavan et al. (2020) highlighted that the correct ratio was essential for maintaining low acid values, reducing the risk of engine corrosion and improving biodiesel's overall stability.

This analysis was important for refining biodiesel production processes, ensuring that the produced fuel met the required standards and enhanced its usability and longevity.

Furthermore, the significant between-group variance relative to within-group variance shown in Table 11 emphasizes the substantial impact of the oil-to-alcohol ratio on biodiesel's water content. These findings highlighted the importance of optimizing the ratio to achieve biodiesel with lower water content, which was critical for fuel quality and performance.

Research highlighted that the alcohol-to-oil ratio was one of the most important parameters for the conversion to biodiesel, influencing the yield and quality significantly. An optimal ratio minimized water content, improving the biodiesel's stability and reducing potential issues related to engine performance (Mittal, 2022). Furthermore, studies showed that the correct ratio could help achieve higher biodiesel yields while reducing impurities, including water content, which was vital for maintaining fuel quality and storage stability (Bashir et al., 2022).

The findings from Tables 1-6 collectively indicated that methanol was the most effective alcohol for biodiesel production, yielding consistent and desirable physicochemical properties across various ratios. Ethanol and 2-propanol were largely ineffective under the tested conditions. This emphasized the necessity of choosing the right alcohol and optimizing the ratio to achieve high-quality biodiesel.

On another hand, Tables 7 to 11 extend the analysis by using ANOVA to statistically assess the significance of differences in the physicochemical properties of biodiesel based on waste cooking oil to alcohol ratios. The ANOVA results from Tables 7-11 collectively confirmed that the ratio of waste cooking oil to alcohol significantly affected key biodiesel properties.

Optimizing these ratios was crucial for maximizing yield, achieving desired pH levels, ensuring consistent density, controlling acid value, and minimizing water content. These insights were vital for refining biodiesel production processes to produce high-quality, efficient, and stable biodiesel.

Table 12 shows the synthesized biodiesel met the European standards (EN14214) for pH, color, density, acid value, and water content. This compliance suggested that the biodiesel was of high quality and suitable for use in diesel engines, ensuring good performance, stability, and minimal risk of damage to the engine and fuel system. These findings underscored the effectiveness of the production process and the suitability of the selected waste cooking oil to alcohol ratios in producing high-quality biodiesel.

The adherence of the synthesized biodiesel to the European Standard Biodiesel specifications

(EN14214) was a testament to the success of the green chemistry approach in this study. By achieving compliance with these standards not only underscored the effectiveness of the production process but also highlights the successful application of green chemistry principles in developing a sustainable and environmentally friendly alternative fuel. The European Standard sets rigorous criteria for biodiesel, including limits on pH, color, density, acid value, and water content, all of which are critical for ensuring that the fuel performs well in engines without causing damage or inefficiencies.

Additionally, the results demonstrated that the chosen waste cooking oil to methanol ratios not only improved biodiesel yield but also contributed to the sustainability of the production process. Using waste cooking oil as a feedstock aligns with green chemistry principles by promoting the recycling of waste materials and reducing the need for virgin raw materials. This approach not only addressed waste management issues but also supports resource conservation, making biodiesel production more sustainable and economically viable. In the context of alternative energy solutions, the application of green chemistry in this study offered notable benefits. It effectively converted waste products into valuable energy sources, mitigating the environmental impact of waste disposal.

Additionally, by meeting established standards and optimizing production conditions, the study demonstrated that biodiesel could serve as a reliable, high-quality alternative to fossil fuels, thereby enhancing its feasibility and appeal as a sustainable fuel.

In summary, the results of this study affirmed the potential of green chemistry in advancing sustainable energy solutions through biodiesel production from waste cooking oil. By optimizing the methanol-to-oil ratio and ensuring compliance with European standards, the research highlighted the effectiveness of green chemistry principles in producing high-quality biodiesel. The study served as a valuable example of how green chemistry could drive innovation and contribute to a more sustainable and eco-friendly energy future.

CONCLUSION

Based on the findings of the study, which assessed the effectiveness of various alcohols—specifically methanol, ethanol, and 2-propanol—in producing biodiesel from waste cooking oil, several key conclusions were drawn. Firstly, methanol was found to be the most effective alcohol for biodiesel production, outperforming the other alcohols tested. The use of higher methanol-to-oil ratios enhanced biodiesel yield, whereas ethanol and 2-propanol either required different conditions or were less suitable for this process. The study further established that methanol, when used at optimal ratios, improved biodiesel yield and provided better control over the physicochemical properties, such as pH and density. However, it was noted that excessively high methanol-to-oil ratios could negatively impact the yield and the color of the biodiesel. The data also confirmed that methanol consistently produced biodiesel with desirable acid values and measurable properties, in contrast to ethanol and 2-propanol, which were less effective in this regard. Additionally, the study highlighted that the waste cooking oil to methanol ratio significantly influenced the key physicochemical properties of the biodiesel. By optimizing this ratio, the quality of the biodiesel was notably improved, with reduced acid content and controlled water levels. Finally, the locally produced biodiesel met the European Standard Biodiesel specifications for pH, color, density, acid value, and water content, confirming its high quality and suitability for use in diesel engines. These results underscored the effectiveness of the production process and affirmed that the chosen waste cooking oil-to-alcohol ratios produced biodiesel with excellent performance and stability.

Furthermore, based on the results of the study, several recommendations were made for those interested in further research. First, it is advised to optimize biodiesel production by refining the use of methanol, particularly by determining the optimal methanol-to-oil ratio, reaction time, temperature, and catalyst concentration to achieve the highest yield and best quality biodiesel. Second, the ratio of methanol in the biodiesel production process should be optimized to control and maintain the desired pH levels, which in turn will improve the quality and stability of the resulting biodiesel. Third, to enhance biodiesel quality, it is recommended to carefully manage the alcohol ratio during production, as higher ratios tend to increase the density of the biodiesel by promoting ester formation and ensuring complete triglyceride conversion. Finally, since the locally produced biodiesel met European standards for pH, color, density, acid value, and water content, it is recommended to continue using this production process along with the chosen waste cooking oil to alcohol ratios. This approach has proven effective in producing high-quality biodiesel that performs well in diesel engines, offering stability and minimizing potential engine damage. Regular adherence to these standards and ratios will help maintain the effectiveness of the biodiesel production process and the quality of the final product.

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