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Biodiesel synthesis from used cooking oil via esterification-transesterification using jackfruit derived waste solid catalysts

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Abstract

The search for renewable and sustainable energy sources has heightened the significance of biodiesel. However, conventional production methods often rely on costly chemical catalysts that produce harmful waste, which this study addresses by introducing a low-cost, recyclable solid catalyst derived from abundant jackfruit peel waste in Indonesia. The novelty of this work lies in transforming underutilized biomass into a functional catalyst that improves both environmental sustainability and economic feasibility. Jackfruit peel was processed through cleaning, drying, grinding, open-air burning, and calcination at 500°C for 120 minutes. The resulting material exhibited significant catalytic activity, with characterization confirming the presence of carbonates and metal oxides, particularly potassium (42.1%). Optimization of the transesterification reaction was carried out using a 1:9 molar ratio of oil to methanol, 12% catalyst loading, and a reaction temperature of 65°C for 105 minutes. Under these conditions, the catalyst achieved a biodiesel yield of 98.9%. The produced biodiesel met the Indonesian National Standard (SNI 7182:2015) for key physicochemical properties. This research highlights the potential of agricultural waste as a sustainable catalyst source, offering an effective pathway toward cleaner biodiesel production and supporting circular economy practices in renewable energy development.

Keywords:
Jackfruit, waste, used cooking oil, catalyst, biodiesel

1 Introduction

As petroleum prices rise and demand for environmentally friendly fuels increases, biodiesel has emerged as a promising alternative energy source due to its competitive cost, low emissions, and ease of production from renewable feedstocks. However, the production of biodiesel still faces challenges related to process efficiency and reliance on conventional catalysts that are less environmentally friendly. This study aims to optimize the transesterification process by utilizing biomass-based solid catalysts to achieve efficient and sustainable biodiesel production. The research addresses the urgent need to reduce dependence on fossil fuels, minimize environmental impacts through waste utilization, and promote energy independence from local renewable resources. Conventional production, however, often depends on expensive chemical catalysts that generate harmful waste [1][2]. To address this challenge, this study introduces a low-cost, recyclable solid catalyst derived from jackfruit peel waste, an abundant byproduct in Indonesia [3]-[8].

This study applies a sustainable economic approach by recycling jackfruit peel waste, a frequently discarded biomass, as a solid catalyst for biodiesel synthesis through transesterification. The strategy focuses on enhancing the catalytic activity and stability of the prepared ash via controlled thermal treatment, thereby improving process efficiency. The use of a solid catalyst facilitates the separation of methyl ester and glycerol through simple filtration, while also minimizing side reactions such as saponification. Furthermore, the environmental impact is mitigated by replacing hazardous chemical catalysts with naturally degradable, waste-derived materials. Catalyst performance is validated by evaluating biodiesel conversion and quality in accordance with Indonesian National Standards (SNI) as well as ASTM D6751. This approach not only reduces production costs by utilizing abundant local waste but also addresses technical challenges associated with purification in homogeneous catalysis. Overall, this innovation exemplifies the principles of green chemistry and aligns with global renewable energy policies that prioritize sustainability.

This research offers several advantages over previous studies, particularly in terms of the novelty of the raw material and technical approach. From the previous study, the jackfruit waste such as seeds or latex has been studied for nutritional or material applications [9]–[11]. Unlike other studies that focus on commercial catalysts or more common biomass sources (such as coconut shells, rice husks, or cocoa peels) [12]–[16], this approach utilizes underutilized agricultural waste, offering a more economical and sustainable solution. This approach utilizes underutilized agricultural waste, offering a more economical and sustainable solution. Furthermore, jackfruit waste or leftover materials demonstrate a versatile capacity to be transformed into a range of products, encompassing bio-oil, seed flour, adsorbents, ethanol, pectin, and even packaging films [4], [5]. Considering these issues, it is essential to investigate and transform such waste into value-added products to minimize environmental pollution and address the problem of peel waste disposal. Based on the literature review, there is a noticeable lack of studies on the development and utilization of jackfruit waste as a solid catalyst in the transesterification process. Numerous research endeavours have focused on examining jackfruit and its derived materials, exploring the potential of distinct elements such as the edible fruit, seeds, peels, and fibrous filaments. A comparison with another research presented in Table 1. Methodologically, this study employs a calcination temperature of 500°C to optimize catalytic activity, a technique rarely tested on jackfruit peel-based catalysts. Furthermore, the direct application to used cooking oil strengthens its practical value within the context of a circular economy.

Table 1. Comparison With Other Biomass-Derived Wastes

Waste-derived biomass for catalyst	Heat/ Calcination treatment	Transesterification parameters			Conversion (%)	Ref.
		O/M ratio	Catalyst weight (wt. %)	Reaction time (minute)		
Cocoa pod husk and plantain peel	300-1100°C 4h	1:15	4.5	90	98.98	[14]
Pineapple leaves	600°C-2h 900°C-1h	1:40	4	30	98	[20]
Sugarcane bagasse	550°C-2h	1:9	10	285	92.84	[21]
Wheat bran	700°C-4h	1:1.46	11.66	114.21	93.6	[22]
Rice straw	700°C-5h	1:15	3.5	150	93.7	[12]
Musa balbisiana colla peel	700°C-4h	1:6	2	180	100	[23]
Jackfruit waste	500°C-2h	1:9	12	105	98.9	Present study

Additional advantages include easier product separation and reduced process waste, addressing common drawbacks associated with conventional homogeneous catalysts [17]–[19]. As such, this research also offers a ready-to-use solution for low-cost biodiesel production.

2 Research methodology

2.1 Catalyst preparation

The preparation of the solid catalyst from jackfruit-derived waste began with the collection, sorting, and cleaning of the raw material, during which the inner part was separated from the outer rind. Both the inner material and rind were dried initially under sunlight for two days, followed by oven drying at 100°C for an additional two days to ensure complete moisture removal. The dried materials were subsequently ground into a fine powder. This powder was combusted in open air, and the resulting ash was collected and separated. The collected ash was a calcination process at 500°C for two hours. The product obtained after calcination served as the solid catalyst, as seen in Fig. 1.

Fig. 1. Catalyst preparation

2.2 Biodesel production

2.2.1 Degumming process

The synthesis process of biodiesel from used cooking oil commenced with a degumming stage aimed at removing phospholipids and other undesirable impurities. In this step, 2% phosphoric acid and distilled water were added to the oil, and the mixture was heated to 70°C while being continuously stirred at 200 RPM on a hot plate for 30 minutes. The acid treatment effectively separated and precipitated phospholipids, gums, and certain metal contaminants, resulting in a cleaner oil suitable for further processing.

2.2.2 Esterification process

Following degumming, the treated oil was subjected to an esterification process to lower its acid value [24], thereby enhancing the efficiency of the subsequent transesterification reaction. Furthermore, feedstocks of inferior quality, particularly those with elevated free fatty acid (FFA) levels exceeding 2% (more than 4 mg KOH/g) such as used cooking oil was typically required a two-stage transesterification process to achieve efficient biodiesel conversion. In the initial esterification step, the FFAs are reacted with an alcohol in the presence of an acid catalyst, resulting in their transformation into esters, thereby reducing the FFA content to a level suitable for subsequent base-catalyzed transesterification. This is followed by a transesterification step using alkaline catalysis to complete the conversion, as illustrated in Fig. 2 [25]. During the esterification step, 2% hydrochloric acid was used as the catalyst, and methanol was introduced in an amount equivalent to three times the molar quantity of oil. The mixture was maintained at 65°C and stirred continuously at 200 RPM on a hot plate equipped with a condenser for 2 hours.

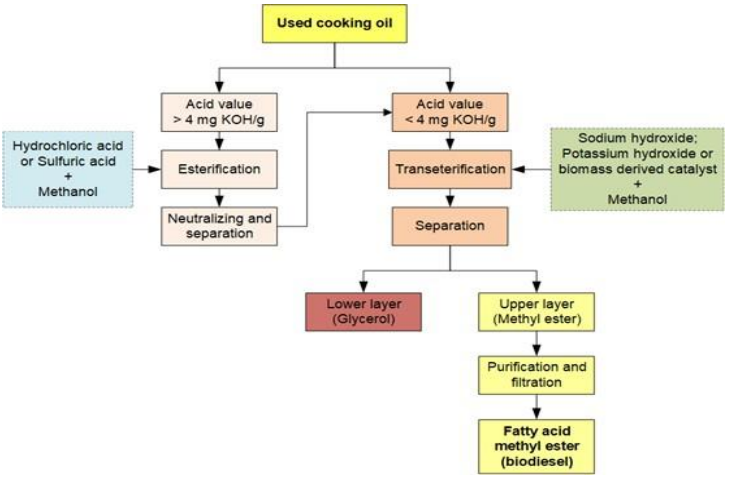

Fig. 2. Two step esterification-transesterification process

2.2.3 Transesterification process

The previous process successfully reduced the free fatty acid content, resulting in pretreated oil suitable for the transesterification stage (as seen in Fig. 3). In this subsequent step, the pretreated oil was combined with methanol and a solid catalyst, with the catalyst loading set at 12% relative to the weight of the oil. The methanol used corresponded to nine times the molar amount of oil. The reaction was conducted at 65°C under continuous stirring at 200 RPM for 1 hour and 45 minutes, ensuring efficient mixing and conversion into biodiesel, utilizing the same hot plate and condenser setupproper conditions for optimal results. The reaction produced fatty acid methyl esters, which were subsequently separated and purified to yield the final product: biodiesel derived from used cooking oil. The flowchart illustrating the stages of the research process is presented in Fig. 4. This paper also includes both ultimate and proximate analyses of jackfruit ash, focusing on its potential as a catalyst precursor.

Fig. 3. Biodiesel synthesis process

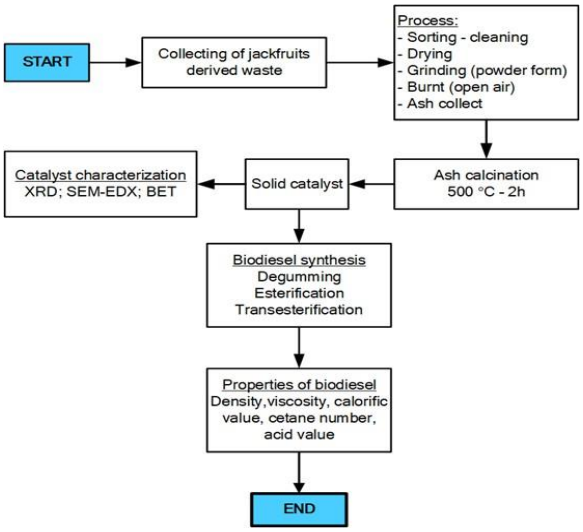

Fig. 4. Flow chart of the research

3 Results and discussion

3.1 Proximate and ultimate analysis

Proximate and ultimate analyses are fundamental techniques employed to characterize the physicochemical composition of materials such as solid fuels, coal, and biomass-derived residues. Proximate analysis quantifies parameters including moisture content, ash, volatile matter, and fixed carbon, offering critical insights into the immediate composition and combustion-related properties of a solid catalyst. In contrast, ultimate analysis determines the elemental composition typically carbon, hydrogen, nitrogen, sulfur, and oxygen providing valuable information on the chemical makeup, energy potential, and suitability of the material for specific catalytic or thermal applications. Together, these analyses enable a comprehensive understanding of the material‟s properties, facilitating its effective utilization in processes such as biodiesel production, energy generation, and waste-to-fuel conversion. In this study, proximate analysis of the prepared jackfruit ash revealed a moisture content of 13.10 wt.%, ash content of 6.26 wt.%, volatile matter of 63.42 wt.%, and fixed carbon of 17.22 wt.%. The ultimate analysis further indicated that the material contained 40.82 wt.% carbon, 6.49 wt.% hydrogen, 1.16 wt.% nitrogen, 0.15 wt.% sulfur, and 45.12 wt.% oxygen. Table 2 shows comparison proximate and ultimate result from others researcher.

Table 2. Comparison Proximate and Ultimate

Catalyst	Properties									Ref.
	Proximate				Ultimate					
	Moisture	Ash	Volatil matter	Fixed carbon	C	H	N	S	O	
Potato peel	8.31	8.6	66.54	16.55	43.85	5.8	3.52	-	46.83	[7]
Musa acuminata peel	8.31	9.85	62.2	19.64	42.43	5.86	2.18	-	49.53	[26]
Rice-straw waste	13.13	13.47	58.34	15.06	33.13	4.92	-	-	49.9	[12]
Orange peel	2.5	6.08	70.56	20.86	5.73	1.93	-	0.005	0.9	[16]
Banana peel	8.6	3.5	75.85	12.05	47.48	6.45	-	0.006	38.7	[16]
Jackfruit waste	13.1	6.26	63.42	17.22	40.82	6.49	1.16	0.15	45.12	Presen study

The results yield significant information regarding the elemental composition and physicochemical characteristics of jackfruit ash. The relatively high volatile matter content suggests a favorable decomposition behavior during calcination, while the low sulfur content minimizes the risk of catalyst poisoning. Additionally, the substantial oxygen and carbon content may enhance surface reactivity, potentially improving catalytic efficiency. Overall, these attributes indicate that jackfruit ash possesses promising characteristics for uses as a catalyst precursor, as they can significantly influence catalytic activity, stability, and overall performance in biodiesel production.

3.2 Solid catalyst characterization

Fig. 5 illustrates the X-ray diffraction (XRD) patterns of the solid catalyst prepared through calcination at 500°C. The observed diffraction peaks at specific 2θ values provide critical insights into the composition and structure of the catalyst. Peaks at 29.7°, 30.8°, 32.3°, and 38.5° confirm the presence of K_2O, while those at 27.3°, 40.4°, 50.2°, and 66.4° indicate KCl. Additional peaks at 26.6°, 33.1°, 36.9°, and 42.8° correspond to Na_2O, K_2CO_3, CaO, and MgO, respectively. Collectively, these results demonstrate the multi-component nature of the catalyst. The elements identified in the solid catalyst have also been reported in previous studies of other waste biomass materials, including pawpaw (*Carica papaya*) peel [27], acai seed [28], plantain peel [29], cocoa pod husk-plantain peel blend [14], *Musa acuminata* peel [26], *Musa paradisiaca* waste [30]. The XRD analysis confirmed the presence of several metal carbonates and oxides. The potassium in the current catalyst, which was the most prevalent component in the form of carbonate, oxide, and chloride, performed an important role in biodiesel synthesis [19][20].

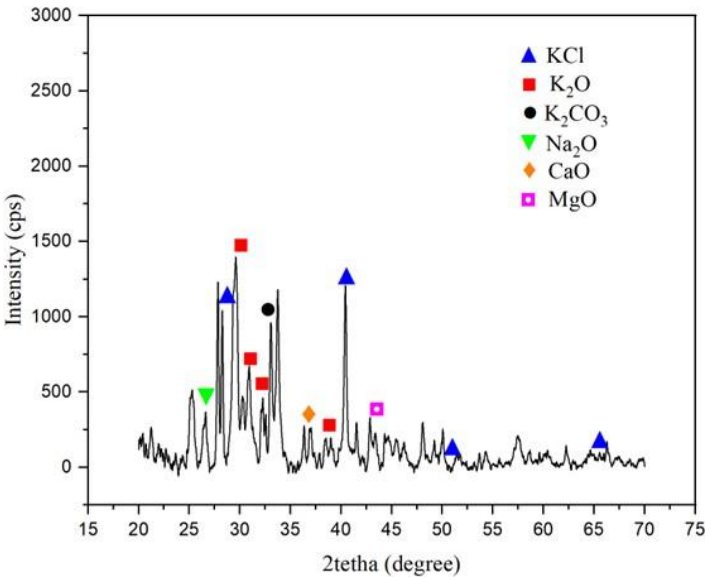

Fig. 5. XRD Pattern of prepared catalyst

SEM analysis revealed that the JPW catalyst surface comprises multiple aggregates with well-defined microporous structures. At magnifications of 5000× (Fig. 6a) and 7500× (Fig. 6b), stratified sheets of varying sizes were observed, exhibiting a glossy appearance along with notable porosity and a spongy texture. These morphological characteristics significantly increase the catalyst's surface area, thereby providing more active sites to enhance catalytic performance. Notably, the SEM images revealed bright particles likely associated with oxidized components in the catalyst, most probably metal oxides. A more detailed understanding of the elemental composition is provided in Figure 7, which indicates that potassium (K) constitutes the primary elemental component of the jackfruit ash produced at 500°C after calcination. This is followed, in decreasing order of abundance, by calcium (Ca) and magnesium (Mg), which together represent the predominant metallic constituents present in the ash. Their respective mass fractions are 42.7%, 6.8%, and 1.8%, amounting 50.6%. The elevated potassium content observed in the sample is particularly significant, as numerous studies have documented that the catalytic performance of biomass-derived solid catalysts, such as calcined jackfruit ash, is strongly influenced by the presence of alkali metals, especially potassium. These elements enhance the basicity of the catalyst surface, thereby promoting the transesterification reaction essential for biodiesel production. Furthermore, the concurrent presence of calcium and magnesium is likely to exert a synergistic effect, improving both the structural stability and the catalytic efficiency of the material. This combination of beneficial metallic constituents highlights the potential of jackfruit ash as a cost-effective and highly active catalyst precursor for sustainable biodiesel synthesis [26], [32]-[34].

In a related investigation, [27] explored the potential of pawpaw (*Carica papaya*) peel ash as a sustainable and eco-friendly solid base catalyst for the production of methyl esters derived from Moringa oleifera oil (MOOME). Upon calcination of the peel ash at 600°C, Energy-dispersive X-ray (EDX) analysis revealed that magnesium (Mg), potassium (K), and calcium (Ca) were the dominant metallic elements, collectively accounting for 27.75% of the mass fraction. This finding aligns with earlier studies on biomass-derived ashes, which have consistently reported elevated levels of alkaline metals especially potassium and calcium that play

a pivotal role in enhancing catalytic efficiency during biodiesel synthesis [28]. Moreover, the work of [32] emphasized the importance of the calcination process, noting that it significantly reduces potassium leaching. This reduction in leaching is crucial, as it improves both the stability and the potential for reuse of the catalyst, thereby enhancing its practical applicability in sustainable biodiesel production.

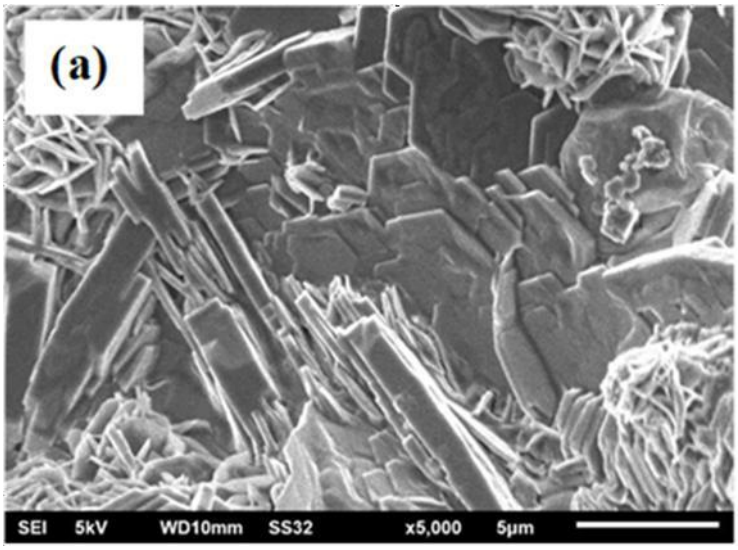

Fig. 6a. SEM analysis with magnification 5000×

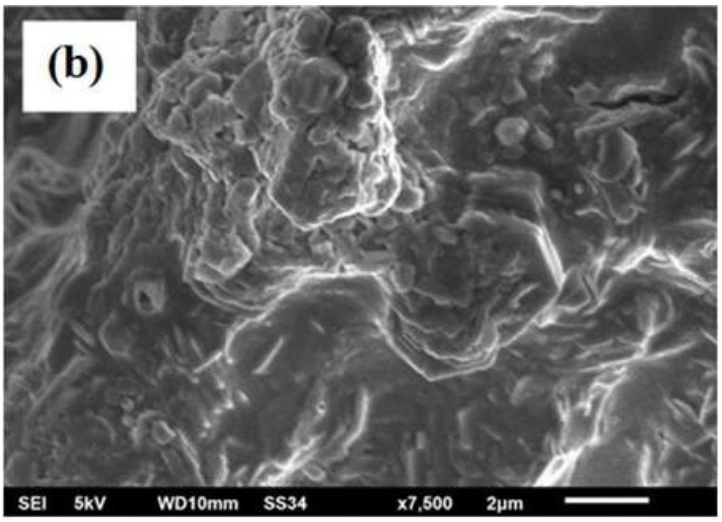

Fig. 6b. SEM analysis with magnification 7500×

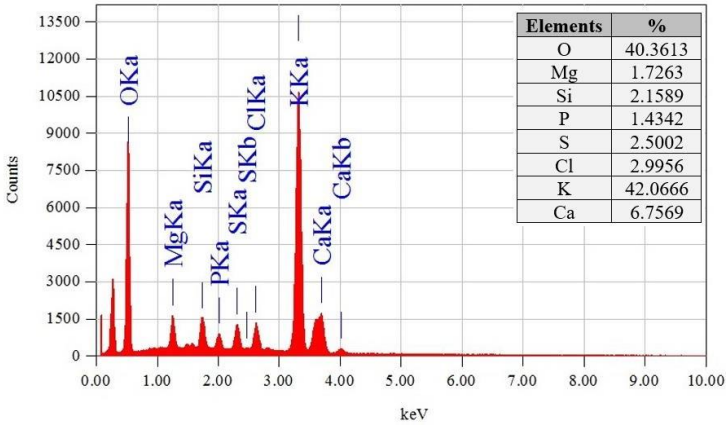

Fig. 7. Elemental composition of jackfruit ash prepared

Furthermore, BET analysis provides valuable information on the specific surface area of a material, which represents the total area available for adsorption or catalytic reactions. In this study, the prepared catalyst showed a specific surface area of 3.74 m²/g, accompanied by an average pore diameter of 25.84 nm and a total pore volume of 0.0242 cm³/g. Further evaluation using the BJH method revealed an average pore volume of 0.0236 cm³/g. These textural properties suggest that the catalyst possesses sufficient surface accessibility to facilitate effective reactant interaction during the transesterification process. Previous research investigated a catalyst prepared from a combination of cocoa pod husk and plantain peel, which was subjected to thermal treatment in a muffle furnace for 4 hours, with calcination temperatures ranging from 300 to 1100°C in 200°C increments. The results indicated that the calcined cocoa pod husk plantain peel ash exhibited a specific surface area of 18.86 m²/g, as determined by BET analysis, while the pore volume, measured using the Barrett–Joyner–Halenda (BJH) method, was found to be 0.04297 cm³/g. The findings indicate that a larger catalyst surface area provides more active sites for the reaction, thereby improving the conversion efficiency of triglycerides into fatty acid methyl esters. In addition, a greater surface area facilitates better mass transfer, reduces diffusion constraints, and helps maintain optimal reaction conditions, all of which lead to an increased biodiesel yield [14]. Table 3 shows comparison of catalyst characteristics with others researcher.

Table 3. Comparison of Catalyst Characteristics

Catalyst	Biodiesel yield	BET Area			XRD	Ref.
		Area (m^2/g)	Pore volume (cm^3/g)	Pore size (nm)		
Orange+ banana peel	98.78	6.5613	0.023712	30.764	2θ = 57.16, 57.40, and 57.08 (KCl)	[16]
Avocado + banana peel	96.06	-	-	-	2θ = 28.90, 39.50, and 68.30 (KCl)	[35]
Banana peel	96.34	13.251	0.025	2.184	2θ = 28.52, 29.75, 33.95, 43.58, 49.02, (K_2CO_3)	[36]
Jackfruit waste	98.9	3.743	0.0242	25.844	29.7°, 30.8°, 32.3°, and 38.5° (K_2 O)	Present study

3.3 Physicochemical properties of biodiesel produced

In this study, we conducted a comprehensive evaluation of the physicochemical properties of the produced biodiesel, focusing specifically on density, viscosity, calorific value, and acid value. Among these parameters, density is particularly significant as it influences fuel atomization and combustion efficiency, while also serving as a metric for estimating the fuel volume necessary to achieve optimal engine performance. Kinematic viscosity reflects the ease of fuel flow, particularly under low-temperature conditions, which directly affects fuel injection and mixing. The acid value serves fuel degradation, and maintaining a low acid value is crucial to prevent corrosion and extend the service life of the fuel system. Together, these parameters provide a thorough understanding of biodiesel"s performance characteristics and its suitability for practical engine applications [28][29]. The physicochemical properties of the produced biodiesel are summarized in Table 4. The density of the biodiesel at 40°C was 870.4 kg/m³, which falls within the acceptable range specified by both SNI 7182:2015 (850–890 kg/m³) and ASTM D6751 (880–900 kg/m³) standards. The kinematic viscosity at 40°C was 3.80 mm²/s, complying with the limits established by SNI (2.3–6.0 mm²/s) and ASTM (1.9–6.0 mm²/s), indicating favorable flow characteristics for engine injection systems. The calorific value of the biodiesel was 39.42 MJ/kg, which is comparable to standard diesel fuels and within the range prescribed by SNI (39.17–44.19 MJ/kg) and ASTM (37–42.5 MJ/kg), suggesting good energy content suitable for combustion applications.

The acid value was measured at 0.411 mg KOH/g, satisfying the maximum limit of 0.5 mg KOH/g set by both standards, indicating effective removal of free fatty acids during processing.

The cetane number of 63.73 exceeds the minimum requirements of SNI (≥ 51) and ASTM (48–65), demonstrating excellent ignition quality and efficient combustion performance. Furthermore, the sulfur content was found to be 2 ppm, significantly lower than the allowable limits in SNI (≤50 ppm) and ASTM (≤15 ppm), confirming that the produced biodiesel is environmentally friendly and suitable for use in diesel engines with low emission requirements. However, owing to its higher oxygen content compared to conventional diesel, biodiesel generally exhibits a slightly lower calorific value, a factor that can influence overall engine performance and fuel efficiency [37].

Tabel 4. Properties of Biodiesel Produced

Properties	Biodiesel		
	Present study	SNI 7182:2015	ASTM D6751 [39]
Density (kg/m^3) at 40°C	870.4	850 – 890	880 – 900
Kinematic viscosity (mm^2/s) at 40°C	3.80	2.3 – 6.0	1.9 – 6.0
Calorific value (MJ/kg)	39.42	39.17 – 44.19	37 – 42.5
Acid value (mg KOH/g)	0.411	Max 0.5	Max 0.5
Cetane number	63.73	Min 51	48 – 65
Sulfur (ppm)	2	Max 50	Max 15

4 Conclusion

In this study, jackfruit-derived biomass was effectively utilized as a renewable and recoverable solid catalyst for the transesterification of used cooking oil into biodiesel. The catalyst demonstrated strong catalytic activity and stability, highlighting its potential as an environmentally friendly alternative to conventional homogeneous catalysts. Elemental analysis revealed a high potassium (K) content of 42.17%, primarily present in the form of carbonates, oxides, and chlorides, along with calcium (Ca) and magnesium (Mg) as alkaline earth metals. The high basicity associated with potassium significantly enhanced the reaction rate and improved the overall conversion efficiency of triglycerides into fatty acid methyl esters (FAMEs). The produced biodiesel exhibited favorable physicochemical properties, with density, viscosity, and acid value all meeting the specifications of SNI 7182:2015 and ASTM D6751 standards. The cetane number exceeded the minimum requirement, indicating efficient combustion, meanwhile the slightly lower calorific value remained within the acceptable range for engine applications. The novelty of this study lies in the valorization of jackfruit waste into a highly active solid catalyst, thereby addressing both waste management and renewable energy challenges simultaneously.

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