



## Review Article

# Agricultural Waste-Based Heterogeneous Catalyst for the Production of Biodiesel: A Ranking Study via the VIKOR Method

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Agricultural waste-based heterogeneous catalysts are emerging as efficient and green catalysts. The present study explored the agricultural waste-based heterogeneous catalyst utilized in the production of biodiesel. The plant waste is composed of organic compounds and various metals which, on combustion, produces ashes that mainly consist of various metal carbonates and oxides. The most commonly employed approach for the solid catalyst preparation from plant materials is the calcination process, and it is performed at temperatures ranging from 300 to 1200°C. It is known that the temperature employed for calcination plays a vital role in the composition and development of the morphology of the catalyst. The variation in alkalinity, porosity, and, accordingly, the catalytic activity of the catalyst is significantly influenced by the calcination temperature. It was found that the potassium present in the form of oxide and carbonate as the main constituent in such catalysts played a significant role in delivering catalytic efficacy. Therefore, a number of agricultural waste-based catalysts were reported as efficient catalysts. The selection of the catalyst may be one of the important issues for application in large-scale biodiesel production. Thus, the present study was undertaken for the preparation of a rank list among the reported catalysts by following the VIKOR (Višekriterijumsko Kompromisno Rangiranje) multicriterion decision-making approach. In this work, the ranking study was performed considering the reported optimum reaction conditions (ORCs) of biodiesel synthesis reactions. The study was conducted strictly on the basis of the parameters, viz., catalyst concentration ( $C_1$ ), MTOR ( $C_2$ ), reaction temperature ( $C_3$ ), reaction time ( $C_4$ ), and biodiesel yield ( $C_5$ ). The parameters are considered good if  $C_1$ ,  $C_2$ ,  $C_3$ , and  $C_4$  are low or minimum and if  $C_5$  is high or maximum. The catalyst prepared from plantain peel showed the best performance and ranked as the first one followed by *Musa paradisiaca* peel and cocoa pod husk catalysts which are ranked second. Thus, the VIKOR method can be useful for comparison and ranking purposes if there are a large number of data, and this may be expanded for thorough study by considering more criteria which may give more fruitful results.

## 1. Introduction

Global energy demand is astonishingly increasing with the growth of the population as well as expansion in urbanization along with industrialization and transportation. Besides

electricity, fuel is the most significant energy source to run modern-day society, and fossil fuels are providing most of the energy demand [1]. Out of the total global energy consumption, 81% is associated with fuel, and 90% of the need is being fulfilled by fossil resources [1, 2]. With regard to

the total worldwide energy consumption, 54% is being spent in the transport sector with an increased average rate of 1.1% yearly, and by 2050, the total energy consumption of the world is estimated to reach 57% [3]. To mitigate the increasing energy demand, a massive amount of fossil fuels is being utilized that leads to the depletion of petroleum reservoirs at a high rate of  $10^5$  times their natural creation, escalating a situation of energy crisis for the near future [1, 4]. It is projected that at the present rate of shrinkage, petroleum resources may be exhausted by 2050, which may create a perilous energy emergency [1, 5]. Furthermore, the combustion of fossil fuels leads to the emission of greenhouse gases that heavily contribute to environmental pollution. Accordingly, human society is pushing itself towards as an environmental threat with increasing global warming [1, 4]. To combat the present dwindling energy sources and environmental concerns, emphasis on the progress of renewable and environmentally benign energy sources for utilization has been strengthened in the last twenty years [6].

There are diverse resources of renewable energy, such as solar, wind, hydro, tidal, biomass and geothermal, and besides biomass, all are being utilized in the generation of electricity rather than fuel. These resources can hardly overcome the contemporary and impending major energy demand for fuel. Therefore, the urgent need for an alternate energy source to combat the scarcity of petrodiesel is a burning issue. In this context, the transformation of biomass to energy, particularly biofuel, is an important field of sustainable alternate energy for the future. Biofuels such as biodiesel, biogas, and bioethanol have appeared as potential renewable fuels that can replace the existing fossil-based fuels [7, 8]. To alleviate the fuel demand of transport and allied sectors, a renewable green fuel that can be directly utilized in diesel engines or mixed with petrodiesel is of high priority. Over the last two decades, biodiesel is gaining global attention as an environmentally friendly and sustainable alternative as it is a biodegradable, nontoxic, carbon-neutral, and renewable fuel [8]. The chemical and fuel properties of biodiesel are also comparable to diesel fuel and provide similar engine performance [9, 10]. Biodiesel is advantageous over conventional fossil fuel as it possesses low viscosity, high flash point, high cetane number, and good lubricity. It contains no sulfur and aromatics, thus resulting in the increase of engine durability as well as reducing the emission of particulate matter, CO, CO<sub>2</sub>, and NO<sub>x</sub> [7, 11, 12]. In addition, biodiesel has a high combustion efficiency that is desirable for longer engine lifespans [13]. However, sustainable growth in the field of alternate energy is dependent on the availability of feedstocks as well as their environment-friendly behaviour along with cost-effectiveness. Depending on the types and sources, biodiesel feedstocks are specified as first-generation, second-generation, third-generation, and fourth-generation feedstocks. The first-generation biodiesel feedstocks are edible oils such as soybean, rapeseed, palm, sunflower, safflower, peanut, corn, coconut, rice bran, hazelnut, castor, mustard, olive, milkweed seed, walnut, linseed, and cotton seed [14–16]. These feedstocks inherently compete with food, and accordingly, their usage as biodiesel feedstock is hotly debated [14]. The second-generation biodiesel sources are nonedible oils such as *Jatropha curcas*, *Thevetia peruviana*, *Pongamia glabra*, *Nicotiana tabacum*, *Crotalaria retusa*, *Simar-*

*ouba glauca*, *Xanthium spinosum*, *Croton tiglium*, rubber tree, neem, *Madhuca indica*, and *Calophyllum inophyllum* [15–18]. These feedstocks can overcome the restrictions of first-generation biodiesel as these are generated from nonedible sources, diminishing the food-versus-fuel debates [19]. The third-generation feedstocks are waste oils/fats from cooking oils, restaurant grease, animal fats, beef tallow, pork lard, poultry fat, chicken fat, as well as algae/microalgae such as *Chlorella* sp., *Chlorella vulgaris*, *Botryococcus braunii*, and *Dunaliella salina* [15, 19, 20]. The third-generation feedstock, microalgae, is not competitive economically in comparison to the first- and second-generation feedstocks due to their low lipid yield and very high production cost as well as expensive oil extraction process [15, 19, 21]. The third-generation feedstock from waste oils needs to be processed before biodiesel production resulting in the addition of supplementary cost in the overall production process [22]. The fourth-generation sources are macroalgae, genetically modified microalgae, and cyanobacteria such as *Chlamydomonas reinhardtii* sp., *Thalassiosira pseudonana* sp., and *Phaeodactylum tricornutum* sp. [15, 16, 19–21, 23]. The fourth-generation biodiesel feedstocks possess very high initial investment and are still in the infancy stage of development [15, 23]. Genetically modified microalgae, the fourth-generation biodiesel feedstock, can overcome the limitation of low lipid yields of third-generation feedstocks by increasing the lipid yield to 35% [19]. The major disadvantage of the fourth-generation biodiesel feedstock is the high risk of leaking genetically modified organisms into the environment which may lead to ecological disruption [21, 24]. However, the energy efficiency of the first-generation biodiesel is comparatively higher than that of other generations [19]. In view of environmental issues, the integration of some or all four generations of biodiesel feedstocks for commercial production seems to be viable [16]. However, to mitigate the potential environmental risk factors, research and development on genetically modified microalgae, as well as advancement of low-cost harvesting techniques, may overcome the difficulties of fourth-generation biodiesel feedstocks. And concerning the present scenario, currently, the second-generation biodiesel feedstock may provide an economic pathway for cost-effective biodiesel production.

Biodiesel is prepared via several ways of which four different approaches have been reported, and these are dilution, pyrolysis or thermal cracking, microemulsion, and transesterification [25, 26]. Transesterification, which is also known as alcoholysis, is one of the most effective and easiest methods for biodiesel generation in which triacylglycerols react with alcohol resulting in esters and glycerol as side-products in the presence of a catalyst [27–29]. Biodiesel is produced mostly by catalytic transesterification of fats or oils with lower alcohols such as methanol, ethanol, propanol, and butanol, of which methanol is most widely used due to its advantageous properties [3, 28, 30–33]. A variety of catalysts such as acid, base, and enzyme are being reported for the production of biodiesel [34, 35]. Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), sulfonic acid (H<sub>2</sub>SO<sub>3</sub>), ferric sulfate (Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>), hydrochloric acid (HCl), phosphoric acid (H<sub>3</sub>PO<sub>4</sub>), organic sulphonic acids, etc., are some of the acid catalysts employed in the reaction of oil [36, 37]. However, homogeneous acid catalysts have drawbacks, such as they

are corrosive, require high pressure and temperature, and need a long reaction time, and accordingly, it is economically daunting to consider the process as efficient in biodiesel production [38–41]. Though a homogeneous base- (NaOH, KOH, NaOCH<sub>3</sub>, etc.) catalyzed reaction requires milder conditions and produces biodiesel in a shorter time with high conversion, the soap formation and issues in catalyst separation from the mixture causing the generation of wastewater are the main limitations of the method [32, 42, 43]. Hence, this process can be considered not feasible for the economical production of biodiesel [7]. Similarly, enzyme-catalyzed transesterification, despite its environmental friendliness and mild reaction conditions, faces economic issues due to the high cost of the enzyme [38, 44].

The heterogeneous base catalysts are performing encouragingly well in biodiesel production and gaining worldwide attention due to their various advantages over homogeneous and enzyme catalysts. These catalysts could produce a good quality product in mild conditions with better efficacy, can be recycled several times easily, and do not produce soap during the reaction, and hence, the entire process is eco-friendly [30, 45–48]. Heterogeneous base catalysts such as metal oxides and mixed metal oxides are reported with higher catalytic activity [49, 50]. Recently, solid catalysts prepared from chemical sources are proven to have good performance in terms of conversion and yield of biodiesel. Some of these reported catalysts are SrO [51], CaO [52, 53], KF/Al<sub>2</sub>O<sub>3</sub> [54], Na/SiO<sub>2</sub> [55], KF/g-Al<sub>2</sub>O<sub>3</sub> [56], KF/ZnO [57], KF-Eu<sub>2</sub>O<sub>3</sub> [58], KOH-Nd<sub>2</sub>O<sub>3</sub> [59], K<sub>2</sub>CO<sub>3</sub>-MgO [60], K<sub>2</sub>CO<sub>3</sub>/CaO [61], Cs-Na<sub>2</sub>ZrO<sub>3</sub> [62], KF/g-Al<sub>2</sub>O<sub>3</sub> [47], Na<sub>2</sub>MoO<sub>4</sub> [63], vanadyl phosphate [64], calcium methoxide [65], sulfated zirconia [66], zirconia-supported tungsten oxide [67], F/hydroxalcite [68], KF/Ca-Mg-Al hydroxalcite [69], calcium ethoxide [48], copper vanadium phosphate [70], MgO [71], Al<sub>2</sub>O<sub>3</sub>-supported metal oxides [72], and Ca-based metal oxides [73]. However, all these catalysts are still unfavorable from an economical viewpoint as these have complex preparation steps such as the incorporation of chemical and then calcination steps that enhances the cost of material preparation, and consequently, the cost of biodiesel production increases [74, 75]. In addition to that, such a catalyst may create disposal issues as they are not eco-friendly since these materials are prepared from nonrenewable sources [7].

Biodiesel production using several CaO-based catalysts from various biomass resources has been reported by many researchers with satisfactory yield. These biomass sources are shrimp shell [76], mussel shell [77], crab shell [78, 79], eggshell [80, 81], *Labeo rohita* scale [82], cockle shell [83], biont shell [84], ostrich eggshell [85], *Turbonilla striatula* shell [86], snail shell [87], clamshell [88], chicken eggshell [89], chicken bone [90], oyster shell [91], animal bones [92], etc. However, these CaO-based catalysts, despite their reactivities in the reaction, possess major drawbacks due to the poisoning of their active sites and storage problems [49, 93]. Accordingly, to overcome such problems, CaO-based catalysts are incorporated with other chemicals, and these loaded catalysts are K<sup>+</sup>/CaO [74], Li/CaO [94], CaO/Na-ZSM-5 [95], CaO/Fe<sub>2</sub>O<sub>3</sub> [75], C/CaO/NaOH [96], Na-C/CaO [97], Mo-Zr/CaO [98], etc. These solid catalysts are reported with good results in terms of yield

and biodiesel conversion. In such cases, the modification of the catalyst is done for stabilization, i.e., the calcined CaO catalysts derived from biomass sources are mixed with the desired chemicals using various methods like wet impregnation, homogenization with aqueous solution, etc., followed by drying and recalcination at a particular temperature [74, 75, 94, 95]. These additional steps along with costly chemicals necessary in the preparation of such an incorporated catalyst increase the cost of the prepared material resulting in the increase of biodiesel production cost. Thus, the development of a stable heterogeneous catalyst from natural sources possessing minimal production cost along with green, environment-friendly, as well as superior catalytic activity has become a challenge in the biorefinery sector for the large-scale production of biodiesel.

In recent years, plant ash-based solid catalysts obtained from various plant wastes and other agricultural waste by-products are gaining popularity among scientists as potential renewable catalysts for biodiesel synthesis. Utilization of such green catalysts can overcome the above-mentioned issues linked to other catalysts. The ash-based materials from waste plants mostly contain alkali, alkaline earth, and other metal carbonates and oxides that display noteworthy efficacy in catalysis with good recyclability. Further, such materials do not possess disposal and storage problems. Therefore, various waste plant-based catalysts in biodiesel synthesis are mainly getting more focus for rigorous research and development. Recently, such reported renewable catalysts in biodiesel synthesis from plant-based sources are tucumã peels [12], coconut husk [99], sugarcane bagasse [100–103], banana peel [104, 105], plantain fruit peel [106], *Musa acuminata* peel [107], *Musa balbisiana* peel [108], *Musa balbisiana* trunk [11], *Musa balbisiana* underground stem [109, 110], *Musa paradisiaca* peel [111], rice husk [112], *Lemna perpusilla* [113], cocoa pod husk [114], wheat husk [115], corncob [116], cotton stalk [117, 118], etc. In these mentioned works, the agricultural-waste-plant-based catalysts presented promising potential in the transformation of oil to biodiesel. As the use of homogenous catalysts is not considered environmentally friendly, utilization of waste biomass-based heterogeneous catalysts is expected for large-scale biodiesel production from an economical viewpoint.

A number of agricultural-waste-plant-sourced catalysts are reported for biodiesel synthesis from various feedstocks. Different agro-waste-based solid catalysts showed different activities in the biodiesel synthesis. Most of the reported catalysts were found to perform satisfactorily. An evaluation of an efficient one among the various reported catalysts is of strategic importance and can play a substantial role in choosing the prominent catalyst for the industrial-scale production of biodiesel. Accordingly, the selection of a proper agricultural waste-based heterogeneous catalyst is of high concern. There have been several methodologies employed for the preplanning and evaluations for the selection of the right candidate. In this regard, multicriterion decision-making (MCDM) approaches are helpful tools in decision-making. Some of the reported MCDM approaches are TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), WSM (Weighted Sum Model), WPM (Weighted Product Model), ANP (Analytical Network Process), AHP (Analytical Hierarchy Process), and

VIKOR (Višekriterijumsko Kompromisno Rangiranje), which are successfully applied in the ranking study [119]. Swathi and Seela [120] reported the application of MCDM approach-based VIKOR and TOPSIS methods for the selection of the best nanoemulsified diesel-biodiesel blend. Swathi et al. [121] also studied the selection of the best biodiesel blend using the AHP approach integrated with the VIKOR method. They reported that the B10 blend nanoemulsified with 100 ppm of  $Al_2O_3$  was the best suitable blend to mitigate the emission to improve the engine efficiency. Fuzzy VIKOR and TOPSIS methods were applied in making the rank of different energy-producing methods considering the economic and environmental viewpoints by Razi and Ali [122] and stated that solar energy is the best source among renewable energies. Abdulvahitoglu and Kilic [119] reported the selection of the most suitable seed oil for biodiesel synthesis in Turkey using the integrated AHP-TOPSIS method. VIKOR and TOPSIS approaches were utilized by Agarwal and Kumar [123] in the selection of the best Karanja biodiesel blend, and they recommended B75 as the best blend. Kumar et al. [124] reported a simplified fuzzy AHP method for evaluating the best biodiesel synthesis method and stated that the supercritical method and microemulsion are the most efficient methods for biodiesel production.

The present study was aimed at applying the VIKOR method in the ranking study of different agricultural waste-based heterogeneous catalysts reported in biodiesel syntheses. The VIKOR method was first presented by Opricovic, which was on the basis of ranking and selecting from a set of alternatives under inconsistent criteria [122]. The VIKOR strategy was designed to optimize the multicriterion complex framework [125]. In the method, the measure of closeness to the ideal alternative was compared, and a compromised ranking could be obtained. This method describes an index that is closer to the positive ideal solution [122]. There are several heterogeneous catalysts from agricultural wastes reported for the production of biodiesel, and various factors govern the optimization for cost-effective production. Considering those factors, the ranking study of the reported catalysts in biodiesel synthesis could be performed to identify the potential and efficient catalyst. It was assumed that by using the VIKOR method, a conclusion can be drawn on the performance of different heterogeneous agricultural wastes for the recommendation of the best catalyst for the biorefinery scale application. The literature survey revealed that the VIKOR method has not yet been used for the ranking study of any catalyst for biodiesel production, and to the best of our knowledge, this would be the first work of a ranking study of the reported heterogeneous catalyst.

The objectives of the present study were to perform an extensive review of the catalytic performance of agricultural waste-based heterogeneous catalysts utilized in biodiesel syntheses and to rank those reported catalysts based on their catalytic performance using the VIKOR method. This study may give a conclusive rank on the catalyst performance considering the selected criteria for the recommendation of a future potential candidate for industrial biodiesel production.

## 2. Agricultural Waste-Based Catalyst Utilized in Biodiesel Production

*2.1. Preparation of Agricultural Waste-Based Catalyst for Biodiesel Synthesis.* Plant-based resources, being renewable, inexpensive, and abundantly available in nature, can play a significant role in the contribution of bio-based chemicals and energy [126]. The utilization of biomass sources as fuels and chemicals reduces pollution with a lower  $CO_2$  output to the atmosphere and results in sustainable and biodegradable products as well [127]. The global scenario currently displays that the total production of biomass exceeded 1.8 trillion tons, which would be a huge resource of energy and other chemicals for the world [128, 129]. The major producer of plant wastes worldwide is the agricultural sector that is followed by waste biomass from the forest [130]. Currently, there are about 140,000 million tons of waste biomass produced from the agricultural sector annually in a global platform per year with a 5–10% rate of increase [131–135]. Reutilization of these biomass wastes is ecologically safe and economical in view of waste-to-wealth conversion and waste management. Proper utilization of these waste by-products to an optimal level is one of the foremost tasks for human society nowadays. Waste plant-based biomasses are composed of cellulose, starch, lignocellulose, lignin, hemicellulose, and oil that are being employed in the generation of platform chemicals, biofuel, and various other value-added products [129, 130, 136, 137]. Utilization of plant-based biofertilizers for sustainable production of crops has been studied and found to be effective with good results [138, 139]. Plant-based wastes have been successfully employed as active precursors and materials for catalyst preparation for various applications [50]. A flow chart showing various applications and value-added products [128, 129, 140] from waste plants is represented in Figure 1.

In recent times, one of the most important applications of the plant wastes is the preparation of solid base catalysts for biodiesel production. Figure 2 exhibits the general preparation method of the catalyst from waste plants. The plant-based material is composed of organic compounds and various metals like Na, K, Ca, and Mg and other elements [7]. The plant-based materials on combustion produce ashes that mainly consist of various metal carbonates and oxides [99, 141]. The most commonly employed approach for the solid catalyst preparation from plant materials is the calcination process, and it is performed at temperatures ranging from 300 to 1200°C for 2–4 h. It is also reported that the temperature employed for calcination plays a vital role in the composition and development of the morphology of the catalyst. The variation in alkalinity, porosity, and, accordingly, the catalytic activity of the calcined catalyst is significantly influenced by the calcination temperature [7, 142]. In this regard, Gouran et al. [115] recently reported the preparation of a catalyst from wheat bran ash and utilized it in biodiesel production from waste cooking oil. Similarly, the preparation of a heterogeneous solid acid catalyst from corncob was investigated for transesterification of algal oil, and a good yield of biodiesel was stated [116]. Sugarcane bagasse waste is also explored as an efficient precursor of the heterogeneous catalyst with good catalytic activity in biodiesel synthesis [100–103]. The cotton

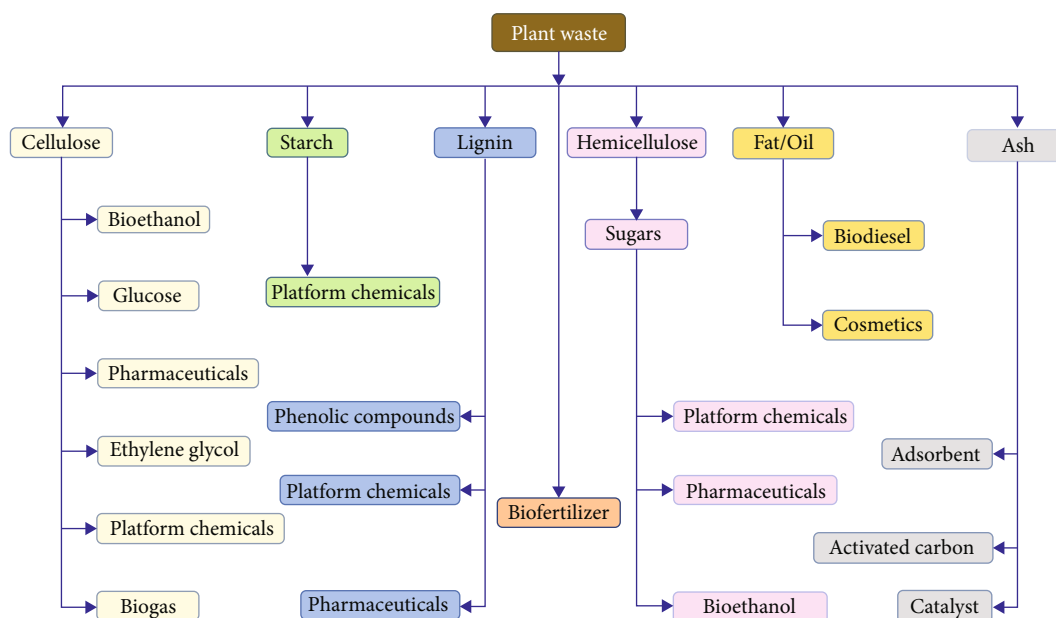


FIGURE 1: Waste plant to sustainable value-added products.

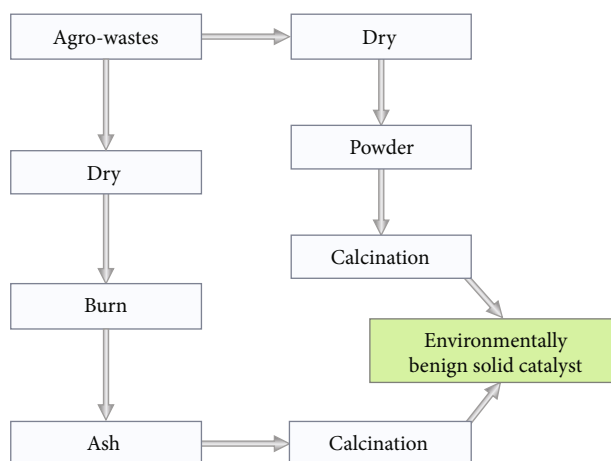


FIGURE 2: Preparation of heterogeneous catalysts from waste plants [135].

stalks generated as waste from cotton-producing farms are compatibly reported as a catalyst in transesterification as well as other reactions [117, 118]. Jute sticks obtained after the removal of jute fiber remains as waste are also efficiently used in the preparation of activated carbon with the potential for use as a catalyst along with other activities [143]. Plantation crops such as tea, coffee, and coconut also generate huge waste that can also be utilized in the generation of catalysts for industrial applications. Akbayrak et al. [144] reported the preparation of catalyst from tea waste and utilized the catalyst in the hydrolysis of ammonia borane. Elabadagama et al. [145] also prepared a heterogeneous catalyst from tea waste and utilized it in the esterification of free fatty acid to biodiesel. Waste coffee residues are successfully utilized in the preparation of catalysts and applied in various applications such as isomerisation of glucose to fructose and esterification [146, 147]. Coconut coir

is also reported in the preparation of heterogeneous catalysts for the preparation of biodiesel [99, 148–150]. Betiku et al. [104], Etim et al. [151], and Falowo et al. [152] reported a calcination temperature of 700°C for the preparation of catalysts from *Musa Gros Michel* fruit, *Carica papaya* peels, and elephant-ear tree pod husk, respectively. Chouhan and Sarma [113] and Sarma et al. [110] reported 550°C as the calcination temperature for the preparation of catalysts from *Lemna perpusilla* Torrey ash and *Musa balbisiana* stem ash, respectively, whereas John et al. [153] reported the calcination at 800°C for ginger leaves in the preparation of the catalyst. Fadara et al. [154] and Oladipto et al. [155] reported calcination temperatures of 400 and 600°C for the catalyst preparation. Studies were found utilizing water extracts of ashes from plant wastes as nonconventional and green catalysts or solvents in several reactions [156]. Because of the basic nature of the waste plant-derived catalysts, they have also been reported as the catalyst in various other reactions like the Dakin reaction [157], Suzuki-Miyaura coupling reaction [158], Henry reaction [159], peptide bond formation reaction [160], as well as *ipso*-hydroxylation reaction [156]. Considering the facts, waste plant residues from the agricultural sector can be investigated as precursors of catalysts for biodiesel production as well as other relevant industrial applications.

**2.2. Composition of Agricultural Waste-Based Catalyst.** Complete combustion of any plant part results in ash material and is composed of inorganic components. Based on the type of sources, the composition of such materials varies and is generally found to consist of oxides and carbonates of metals such as  $K_2O$ ,  $K_2CO_3$ ,  $KCl$ ,  $CaO$ ,  $SiO_2$ ,  $MgO$ ,  $Fe_2O_3$ ,  $P_2O_5$ , and  $Al_2O_3$  [7, 50, 140, 161]. The literature disclosed that these materials possessed a highly basic character [110, 141, 156, 158] and exhibited good catalytic efficacy in biodiesel production [12, 110, 114]. Thus, the presence of a higher percentage of carbonate and oxide of potassium in the catalyst is accountable for

making it an alkaline, resulting in good efficiency as a catalyst in biodiesel production. The elemental compositions of various waste plant-derived heterogeneous catalysts reported in biodiesel synthesis are listed in Table 1 and reveal that most of the catalysts prepared from waste plant sources possess a higher percentage of K compared to other metals. The highest potassium content of 99.73% was reported by Betiku et al. [104], where the presence of oxygen and carbon was not reported. Eldiehy et al. [162] reported 65.45% of potassium content in sweet potato generated catalysts, where the presence of oxygen and carbon is also not reported. Comparable potassium content for catalysts generated from *Musa paradisiaca* peel (54.73%) [111], *Musa paradisiaca* peel (51.02%) [106], *Tectona grandis* leaves (53.25%) [163], and cocoa pod husk + plantain peel (51.94%) [164] is observed from Table 1. Li et al. [165] reported a very low potassium content of 1.12% in camphor-tree-leaf-derived catalysts. A good percentage of oxygen and carbon along with potassium in the catalysts supports the presence of oxide and carbonates of potassium, which are stated to play the key role in the activity of the catalyst in the transesterification of vegetable oil to biodiesel. The composition of the plant ashes listed in Table 1 reveals the variability in the concentration of metal components in different plant species reported by the researchers. The chemical composition of a plant species or a particular plant-derived ash is found to vary and cannot be precisely defined [166]. The chemical composition of the plant ashes depends on various factors such as type of plant and species, maturity of the plant, seasonal variance, type of soil, climatic conditions, geographical conditions and altitude of plant growth, and ash preparation conditions such as burning and calcination processes [135, 166–168]. The plant mineral composition is also regulated by the soil pH which influences the mineral and nutrient acquisition of plants and, accordingly, the plant ash [169]. Harvesting condition, contaminants, age, and maturity of the plant are also some of the factors that influence the mineral composition of the plant even within a single plant species [166, 167]. Thus, generalization of the chemical content of ash of a plant species is difficult due to its variability [167]. A single plant species may result in ash containing different types of metal as well as chemical composition. Analysis of the ash materials for chemical composition is found to be crucial before drawing a conclusion on its mineral composition.

**2.3. Catalytic Performance of Agricultural Waste-Based Catalyst in Biodiesel Synthesis.** In recent times, plant wastes from postharvested agricultural products are widely explored for value-added products, and one of the important applications of the plant wastes is the utilization of catalyst precursors for biodiesel production. Plant waste-derived catalysts are easy to handle, simple to prepare, easily available, less toxic, biodegradable, cost-effective, and eco-friendly. The biodiesel synthesis using the catalysts prepared from different agricultural waste products with their performance are summarized in Table 2. These reported catalysts are *Musa balbisiana* stem [110], *Musa balbisiana* stem [109], *Musa balbisiana* peel [108], *Musa balbisiana* trunk [11], *Musa paradisiaca* peel [111], *Musa paradisiaca* fruit peels [106], ripe banana (*Musa* “Gros Michel”) fruit peels [104],

cocoa pod husk and banana peel [105], flamboyant pods [170], *Lemna perpusilla* Torrey [113], *Acacia nilotica* tree stem [142], cocoa pod husk [114], Birch bark [171], coconut husk [99], etc.

Recently, Jitjamnong et al. [172] studied the effect of calcination temperature on heterogeneous base catalysts derived from desert banana peel. They prepared the catalyst by drying the banana peel in an oven followed by calcination at different temperatures ranging from 550 to 650°C. The 600°C calcined catalyst showed a high percentage of K, Ca, Mg, and P and exhibited the highest catalytic activity. The transesterification was carried out via microwave irradiation with soybean oil, and the 99.3% FAME yield was reported in 2 min with the optimum reaction conditions (ORCs) of 1 wt.% of catalyst amount and 12:1 MTOR (methanol-to-oil ratio). The reusability study showed good reusability up to the fourth run with 80.7% of yield. Changmai et al. [173] examined the catalytic performance of a heterogeneous catalyst prepared from orange peel in the transesterification of soybean oil to biodiesel. The EDX analysis of the catalyst showed an increase in potassium content from 0.18% to 14.67% from dried orange peel to orange peel ash. A good surface area of 605.60 m<sup>2</sup> g<sup>-1</sup> with a mesoporous structure was obtained for orange peel ash. They reported 98% of conversion at ORCs of 7 wt.% of the catalyst load and 6:1 MTOR in a reaction time of 7 h. The catalyst was successfully reused up to the fifth cycle with a biodiesel conversion of 85%. *Tamarindus indica* fruit shell ash was investigated as a heterogeneous catalyst for biodiesel synthesis from *Parinari curatellifolia* oil by Nabora et al. [174]. The oven-dried shell is calcined at 800°C to prepare the catalyst. The catalyst showed high basicity with a surface area of 378 m<sup>2</sup> g<sup>-1</sup>. At ORCs of 5 wt.% catalyst loading, 9:1 MTOR, and reaction temperature of 60°C, a good biodiesel yield of 96.2% was reported in a reaction time of 120 min. The catalyst reusability showed 74% of yield at the fourth run of the reaction. Miladinović et al. [175] reported the catalytic activity of walnut shell ash in the sunflower oil methanolysis for biodiesel production. They prepared the catalyst via combustion of the dried shell followed by calcination at 800°C for 2 h. The ORCs were reported to be 5 wt.% of the catalyst loading, 12:1 MTOR, and 60°C reaction temperature yielding 98% of biodiesel in a reaction time of 10 min. The regeneration of catalytic activity was done by recalcination at 800°C for 2 h and reused up to the fourth run. Gohain et al. [163] prepared a heterogeneous catalyst from *Tectona grandis* leaves and applied it in waste cooking oil biodiesel production. Catalyst preparation was done via calcination of the dried leaves at 700°C for 4 h. 100% conversion of oil to biodiesel was reported in 180 min with 2.5 wt.% of the catalyst loading and 6:1 MTOR at room temperature.

Oladipto et al. [155] investigated the activity of a heterogeneous catalyst prepared from *Carica papaya* peel in morning oil methanolysis. The catalyst preparation was done via calcination of the air-burnt peels at 200–1000°C, and 600°C is reported as the best temperature resulting in the highest percentage of active components. The Taguchi orthogonal array approach was applied to identify the ORCs which were reported to be 3.5 wt.% of the catalyst loading, 9:1 MTOR,

TABLE 1: Chemical/elemental composition of catalyst derived from agricultural waste plants.

Source of catalyst (ash)	Calcination with time	Composition (%)											References		
		Na	K	Ca	Mg	Mn	Fe	Zn	Al	P	Si	Cl		C	O
<i>Acacia nilotica</i> tree stem	500°C, 3 h	0.6	6.7	13.3	2.7	—	—	—	8.3	0.80	15.7	—	—	—	[142]
<i>Acacia nilotica</i> tree stem	800°C, 3 h	5.7	5.7	17.8	4.5	—	—	—	1.2	0.5	21.5	—	—	[142]	
<i>Lemna perpusilla</i> Torrey	550°C, 2 h	0.53	11.32	—	—	—	—	—	—	—	82.51	1.10	5.10	[113]	
<i>Musa balbisiana</i> underground stem	550°C, 2 h	0.61	25.09	10.44	10.04	—	1.88	—	4.07	4.47	35.92	—	—	[110]	
<i>Musa paradisiaca</i> peels	500°C, 3.5 h	—	54.73	1.13	—	0.05	0.04	0.01	3.42	1.99	33.01	4.89	—	[111]	
Banana ( <i>Musa Gros Michel</i> ) peels	700°C, 4 h	0.19	99.73	0.03	0.03	0.01	0.01	0.004	—	—	—	—	—	[104]	
<i>Musa balbisiana</i> peels	700°C, 4 h	10.41	41.37	36.08	12.02	—	—	—	—	—	—	—	—	[108]	
Cocoa pod husk	700°C, 4 h	—	59.2	—	3.0	—	—	—	—	0.8	0.3	—	36.2	[114]	
<i>Musa paradisiaca</i> peels	700°C, 4 h	—	51.02	—	1.15	—	—	—	0.29	1.84	2.51	6.27	36.43	[106]	
Camphor tree leaf	800°C, 2 h	0.23	1.22	12.05	1.82	—	—	—	2.70	—	—	—	—	[165]	
Orange peel	Burnt	—	14.67	7.34	2.02	—	—	—	—	1.57	—	—	32.50	40.86	[173]
<i>Tectona grandis</i> leaves	700°C, 4 h	1.67	53.25	30.28	4.77	—	—	—	—	—	10.03	—	—	—	[163]
<i>Carica papaya</i> peel	700°C, 3 h	0.82	30.74	3.64	1.16	—	—	—	—	4.22	0.71	10.3	—	44.1	[151]
<i>Carica papaya</i> peel	600°C, 4 h	0.0	23.89	2.86	1.00	—	0.0	—	—	3.04	0.0	0.87	29.16	36.72	[155]
Moringa leaves	500°C, 2 h	—	9.87	10.09	5.92	—	—	—	—	1.19	—	—	13.19	59.57	[177]
Cocoa pod husk + plantain peel	700°C, 4 h	0.0	51.94	0.0	2.05	—	0.0	—	—	1.04	1.01	2.77	—	40.93	[164]
<i>Mangifera indica</i> peel	Burnt	0.25	43.89	9.44	3.07	—	0.46	—	—	4.21	2.61	—	2.38	32.54	[178]
Wheat straw	Burnt	—	7.7	1.5	1.1	—	—	—	—	—	18.2	1.3	41.4	28.9	[180]
<i>Carica papaya</i> trunk	400°C, 4 h	0.63	23.85	15.40	1.78	—	—	—	—	2.85	0.0	1.18	—	51.34	[154]
<i>Musa paradisiaca</i> peel	700°C, 4 h	—	20.95	—	—	—	—	—	—	—	—	8.06	49.48	10.98	[202]
<i>Musa acuminata</i> flower petal	Burnt	—	45.44	2.4	3.05	—	—	—	—	2.03	1.95	—	1.9	41.84	[184]
Plantain peels	500°C, 4 h	—	45.16	—	3.61	—	—	—	—	—	—	—	—	35.34	[185]
Hazelnut shell	800°C, 2 h	—	26.29	11.62	6.77	—	—	—	—	6.10	—	—	—	—	[190]
Potato peel	700°C, 3 h	1.85	36.54	2.71	2.02	0.45	1.30	0.10	—	—	3.06	1.24	9.18	41.55	[189]
Sweet potato leaves	900°C, 3 h	0.70	65.45	18.02	4.63	—	0.88	—	0.94	—	3.54	4.12	—	—	[162]
<i>Musa paradisiaca</i> peel	550°C, 2 h	—	29.25	4.01	1.08	—	—	—	—	1.06	3.81	3.01	24.02	33.34	[183]
<i>Musa paradisiaca</i> trunk	550°C, 2 h	—	36.31	2.21	3.08	—	0.59	—	0.63	1.12	2.84	2.13	13.22	37.87	[183]
<i>Musa paradisiaca</i> rhizome	550°C, 2 h	—	30.06	3.06	0.69	—	—	—	—	1.00	1.67	1.83	18.43	43.27	[183]
Sugarcane bagasse	550°C, 2 h	0.60	12.07	2.43	1.12	—	0.25	—	0.24	2.14	24.11	—	5.89	50.22	[103]
<i>H. fragrans</i>	550°C, 2 h	—	19.05	5.13	0.86	—	—	—	0.44	0.64	8.51	1.92	16.71	46.74	[203]

TABLE 2: Performance of agricultural waste plant-based heterogeneous catalysts in biodiesel synthesis from various oil feedstocks.

Biodiesel feedstock	Source of catalyst (ash)	Surface area ( $\text{m}^2 \text{g}^{-1}$ )	Parameters				Time (min)	Biodiesel, Y or C (%)	References
			Catalyst load (wt.%)	MTOR	Temp ( $^{\circ}\text{C}$ )				
Jatropha oil	Coconut husk	—	5	12:1	45	60	99.77 (Y)	[99]	
<i>Thevetia peruviana</i> oil	<i>Musa balbisiana</i> trunk	1.487	20	20:1	32	180	96 (Y)	[111]	
<i>Jatropha curcas</i> oil	<i>Acacia nilotica</i> tree stem	3.72	5	12:1	65	180	98 (C)	[142]	
<i>Jatropha curcas</i> oil	<i>Lemna perpusilla</i> Torrey	9.622	5	9:1	65	300	89.43 (C)	[113]	
<i>Jatropha curcas</i> oil	<i>Musa balbisiana</i> underground stem	38.71	5	9:1	275	60	98 (C)	[110]	
<i>Mesua ferrea</i> oil	<i>Musa balbisiana</i> underground stem	38.71	5	9:1	275	60	95 (C)	[109]	
<i>Thevetia peruviana</i> oil	<i>Musa paradisiaca</i> peels	—	3	10:3	60	90	95.25 (Y)	[111]	
<i>Bauhinia monandra</i> oil	Banana ( <i>Musa Gros Michel</i> ) peels	4.442	2.75	7.6:1	65	69	98.5 (Y)	[104]	
Palm oil	Birch bark	—	3	12:1	60	180	69.7 (C)	[171]	
Waste cooking oil	<i>Musa balbisiana</i> peels	10.176	2	6:1	60	180	100 (C)	[108]	
<i>Azadirachta indica</i> oil	Cocoa pod husk	2.76	0.65	3:2.2	65	57	99.3 (Y)	[114]	
<i>Azadirachta indica</i> oil	<i>Musa paradisiaca</i> peels	18.80	0.65	3:2.2	65	57	99.3 (Y)	[106]	
Palm kernel oil	Banana fruit peels	—	4	3:2.4	65	65	99.96 (Y)	[105]	
Palm kernel oil	Cocoa pod husk	—	4	3:2.4	65	65	100 (Y)	[105]	
<i>Parinari curatellifolia</i> oil	<i>Tamarindus indica</i> fruit peel	378	5	9:1	60	120	96.2 (Y)	[174]	
Sunflower oil	Walnut shell	8.8	5	12:1	60	10	98 (Y)	[175]	
<i>Moringa oleifera</i> oil	<i>Carica papaya</i> peel	3.6042	3.5	9:1	35	40	96.43 (Y)	[155]	
Soybean oil	Moringa leaves	—	6	6:1	65	120	86.7 (Y)	[177]	
Honne oil	Cocoa pod husk + plantain peel	18.86	4.5	15:1	65	150	98.98 (Y)	[164]	
Sunflower oil	Ginger leaves	0.834	1.6	6:1	60	90	90.13 (Y)	[153]	
Palm oil	Spent coffee	—	4.94	6.68:1	65	82.42	97.08 (Y)	[204]	
Soybean oil	<i>Mangifera indica</i> peel	123.34	6	6:1	28	240	98 (Y)	[178]	
Refined soybean oil	Pineapple leaves	—	4	40:1	60	30	98 (C)	[179]	
Palm oil	<i>Musa sapientum</i> peel	—	4	15:1	65	120	99.16 (Y)	[205]	
<i>Hevea brasiliensis</i> oil	Kola nut pod husk	—	3.5	6:1	65	75	96.77 (Y)	[176]	
Sunflower oil	Wheat straw	98.5	11.6	18.3:1	60.3	124	98.6 (Y)	[180]	
Soybean oil	Acai seed	—	12	18:1	100	60	98.5 (Y)	[181]	
Waste cooking oil	Sugarcane bagasse	20.78	5	15:1	60	15	92.12 (Y)	[206]	
<i>Madhuca indica</i> oil	Banana pseudostem	4.58	5.9	14.9:1	60	178.1	98.8 (C)	[182]	
Waste cooking oil	Wheat bran	—	11.66	1.46:1	54.6	114.21	93.6 (Y)	[115]	
Waste cooking oil	<i>Musa acuminata</i> flower petal	79.33	5.63	6.24:1	28	221	99.99 (C)	[184]	



TABLE 2: Continued.

Biodiesel feedstock	Source of catalyst (ash)	Surface area ( $\text{m}^2 \text{g}^{-1}$ )	Parameters			Biodiesel, Y or C (%)	References
			Catalyst load (wt.%)	MTOR	Temp ( $^{\circ}\text{C}$ )		
Waste cooking oil	Plantain peel	1.10	0.5	6:1	45	97.96 (Y)	[185]
Yellow oleander + rubber oil	Cocoa + kola nut + pumpkin	17.266	1.5	9:1	55	95.02 (Y)	[186]
<i>Luffa cylindrica</i> , <i>Datura stramonium</i> , and <i>Lagenaria siceraria</i> oils	<i>Musa acuminata</i> and <i>Citrullus lanatus</i> peels	—	3.53	9:1	90	96.63 (Y)	[187]
Waste cooking oil	Hazelnut shell	4.9	5	12:1	60	98 (Y)	[190]
Waste cooking oil	Potato peel	23.5	3	9:1	60	97.5 (C)	[189]
Waste cooking oil	<i>Musa acuminata</i> peel	12	1.5	9:1	60	98 (C)	[188]
Microalgal oil	Sweet potato leaves	2.81	7	15:1	60	99.5 (C)	[162]
Waste cooking oil	Sweet potato leaves	2.81	5	9:1	60	98 (C)	[162]
Jatropha oil	<i>Musa paradisiaca</i> peel	4.1	5	9:1	65	97.56 (Y)	[183]
Jatropha oil	<i>Musa paradisiaca</i> trunk	6.4	5	9:1	65	97.65 (Y)	[183]
Jatropha oil	<i>Musa paradisiaca</i> rhizome	7.0	5	9:1	65	95.67 (Y)	[183]
Jatropha oil	Sugarcane bagasse	7.66	10	9:1	65	92.84 (Y)	[103]
Jatropha oil	<i>H. fragrans</i>	27.50	7	12:1	65	97.75 (Y)	[203]
Sunflower oil	<i>Sesamum indicum</i>	3.66	7	12:1	65	98.9 (Y)	[207]
Soybean oil	<i>Brassica nigra</i>	7.308	7	12:1	65	98.79 (Y)	[208]
Soybean oil	<i>Brassica nigra</i>	7.308	7	12:1	32	98.87 (Y)	[208]
Jatropha oil	<i>Brassica nigra</i>	7.308	7	12:1	65	98.26 (Y)	[208]
<i>Thevetia peruviana</i> oil	<i>Brassica nigra</i>	7.308	7	12:1	65	97.78 (Y)	[196]

MTOR: methanol-to-oil ratio; Temp: temperature; min: minute; Y: yield; C: conversion.

and 35°C reaction temperature resulting in a biodiesel yield of 96.43% in 40 min. Oladiplo and Betiku [176] also investigated the catalytic activity of a heterogeneous catalyst derived from kola nut pod husk for transesterification of rubber oil to biodiesel. The ORCs reported were 3.5 wt.% of the catalyst loading, 6:1 MTOR, and 65°C reaction temperature. A biodiesel yield of 96.97% was obtained in 75 min. Aleman-Ramirez et al. [177] prepared a catalyst from moringa leaf and utilized it in soybean oil biodiesel production. Inorganic components of dolomite,  $K_2Ca(CO_3)_2$ , and calcite were the compositions of the catalyst after calcination. The reported ORCs were 6 wt.% of the catalyst loading and 6:1 MTOR at 65°C that yielded 86.7% of biodiesel in 120 min. Olatundun et al. [164] reported the blending of cocoa pod husk and plantain peel for the preparation of heterogeneous catalysts for biodiesel production. The catalyst was prepared by separately burning the cocoa pod husk and plantain peel to ash, mixing them in equal amounts, and subjecting them to calcination at different temperatures (300–1000°C). The key active components K and Ca were found to be the highest during calcination at 500°C that was considered as the optimum temperature. The best reported operating conditions resulting in the highest biodiesel yield of 98.98% were 4.5 wt.% of the catalyst loading and 15:1 MTOR at 65°C in a reaction time of 150 min. John et al. [153] investigated the transesterification of soybean oil using a heterogeneous catalyst derived from waste ginger leaves. They prepared catalysts from the oven-dried leaves following three different methods, viz., (i) calcination at 800°C for 2 h, (ii) potassium hydroxide activation, and (iii) sodium hydroxide extraction. The ORCs for transesterification were reported to be 1.6 wt.% of the catalyst load and 6:1 MTOR at room temperature with 200 rpm. A biodiesel yield of 90.13% in a reaction time of 90 min was reported for the calcined ginger leaf catalyst. Waste *Mangifera indica* peel was investigated as a catalyst source by Laskar et al. [178] in soybean oil biodiesel production. The surface area of the prepared catalyst was reported as 123.34 m<sup>2</sup> g<sup>-1</sup>. The characterization of the catalyst showed the presence of 59.14% of potassium and reported that K<sub>2</sub>O played a vital role in the catalytic activity. The ORCs reported were 6 wt.% of the catalyst and 6:1 MTOR at room temperature (28°C) resulting in a biodiesel yield of 98% in a reaction time of 240 min. Similarly, Barros et al. [179] examined the catalytic activity of the catalyst derived from pineapple leaves in soybean oil biodiesel synthesis. The catalyst was prepared via calcination of the oven-dried leaves at 600°C for 2 h and then at 900°C for 30 min. 4 wt.% of the catalyst loading with 40:1 MTOR at 60°C were reported as ORCs with a 98.2% biodiesel yield in 30 min. The catalyst was reused up to the fourth run of the reaction with an 85% biodiesel yield.

Veličković et al. [180] investigated the catalyst prepared from wheat straw ash in sunflower oil biodiesel production. The catalyst preparation was performed by burning the dried straw in open air. The BET surface area of the wheat straw ash catalyst was reported to be 98.5 m<sup>2</sup> g<sup>-1</sup>. A good biodiesel yield of 98% was obtained in 124 min at the ORCs of 11.6 wt.% of the catalyst loading and 18.3:1 MTOR at a 60.3°C reaction temperature. A very sharp decrease of biodiesel yields to 37%, 12%, and 3% on the second, third, and fourth runs of reactions, respectively, was noticed. Mares et al. [181]

studied the biodiesel production from soybean oil using a heterogeneous catalyst prepared from Acai seed ash via calcination at 500–900°C of which 800°C for 4 h resulted in the best performance. The ORCs for the synthesis of biodiesel were 12 wt.% of the catalyst loading and 18:1 MTOR at 100°C that yielded 98.5% of biodiesel at a reaction time of 60 min. The catalyst characterization portrayed the presence of oxides and carbonates of potassium and calcium as the key active component. The reusability study showed an 80% biodiesel yield at the fourth reaction cycle. A catalyst prepared from Poovan banana pseudostem was studied by Niju et al. [182] for the biodiesel synthesis from *Madhuca indica* oil. They prepared the catalyst by drying the pseudostem followed by calcination at 700°C for 4 h. The surface area of the catalyst was 4.850 m<sup>2</sup> g<sup>-1</sup>. Response surface methodology was employed to optimize the conditions, and a biodiesel yield of 98.8% was achieved in 178.1 min using 5 wt.% of the catalyst loading, 14.9:1 MTOR, and a 65°C reaction temperature. Gouran et al. [115] reported the heterogeneous catalyst from wheat bran ash for biodiesel synthesis from waste cooking oil. A biodiesel yield of 93.6% was reported using 11.66 wt.% of the catalyst loading and 1.46:1 MTOR at 54.6°C for 114.21 min. Basumatary et al. [183] reported heterogeneous base catalysts from *Musa paradisiaca* peel, trunk, and rhizome for the synthesis of *Jatropha curcas* oil biodiesel. Characterization of the catalyst revealed the surface areas of 4.1, 6.4, and 7.0 m<sup>2</sup> g<sup>-1</sup> and high potassium content of 36.31, 30.06, and 29.25% in peel, trunk, and rhizome catalysts, respectively. The *Musa paradisiaca* trunk which had the highest pH and basicity compared with the peel and rhizome showed the highest catalytic activity exhibiting a turnover frequency of 68.24 min<sup>-1</sup>. The ORCs reported were 5 wt.% of the catalyst loading, 9:1 MTOR, and a 65°C reaction temperature resulting in a 97.65% biodiesel yield in a short duration of 9 min. Basumatary et al. [103] also investigated a sugarcane bagasse-derived heterogeneous catalyst for *Jatropha* biodiesel synthesis. The catalyst was prepared via calcination at 550°C for 2 h. Catalyst characterization showed the presence of 12.07% of potassium. Low potassium revealed a lower catalytic activity at ORCs of 10 wt.% of the catalyst, 9:1 MTOR, and a 65°C reaction temperature that yielded 92.84% of biodiesel in 285 min with a turnover frequency (TOF) of 6.59 h<sup>-1</sup>. Laskar et al. [184] also studied the preparation of a heterogeneous catalyst from *Musa acuminata* flower petals for biodiesel production from waste cooking oil. The catalyst preparation was done by open-air burning of the dried petal. The characterization of the catalyst showed the presence of a highly basic K<sub>2</sub>O (60.23%) that was responsible for catalytic activity. The catalyst with a BET surface area of 79.33 m<sup>2</sup> g<sup>-1</sup> showed good catalytic activity with 99.99% conversion at the ORCs of 5.63 wt.% of the catalyst loading, 6.24:1 MTOR, and 4 h of reaction time at room temperature.

Falowo et al. [185] described biodiesel production using the catalyst prepared from the mixture of unripe and ripe plantain peels via calcination of dried peels at 500°C. The ORCs were found to be 0.5 wt.% of the catalyst, 6:1 MTOR, and a 45°C reaction temperature with a biodiesel yield of 97.96%. K content of 45.16% was revealed from the catalyst characterization along with a low surface area of 1.10 m<sup>2</sup> g<sup>-1</sup>. Falowo and Betiku [186] also studied the preparation of a

heterogeneous catalyst from kola nut, cocoa, and fluted pumpkin waste and utilized it in the transesterification of an oil blend of rubber and yellow oleander. The catalytic activity was reported due to an abundant concentration of potassium (48.4%). The oil blend was first esterified and then transesterified with an optimum catalyst loading of 1.5 wt.% and 9:1 MTOR at a 65°C reaction temperature resulting in 95.02% biodiesel in 40 min. Similarly, Adepoju et al. [187] prepared a heterogeneous catalyst from a mixture of three agro-waste peels, viz., *Cucurbita pepo*, *Citrullus lanatus*, and *Musa acuminata* and utilized it in the transesterification of a vegetable oil blend of *Datura stramonium*, *Lagenaria siceraria*, and *Luffa cylindrica*. The characterization of the catalyst showed a high percentage of CaO (75.65%) in the mixture compared to individual *Cucurbita pepo* (62.83%), *Musa acuminata* (65.50%), and *Citrullus lanatus* (58.67%) calcined catalysts. The mixture catalyst resulted in the highest biodiesel yield of 97.20% compared to the *Cucurbita pepo* (83.50%), *Musa acuminata* (88.75%), and *Citrullus lanatus* (80.32%) catalysts. The reported ORCs were 3.53 wt.% of the catalyst loading, 9:1 MTOR, a 90°C reaction temperature, and 80 min of reaction time. *Musa acuminata* peel was also utilized in the preparation of a heterogeneous catalyst by Daimary et al. [188] and applied to soybean waste cooking oil biodiesel production. The reported ORCs were 1.5 wt.% of the catalyst and 9:1 MTOR at 60°C that resulted in the biodiesel yield of 98.0% in 120 min. Daimary et al. [189] also reported the preparation of a solid catalyst from potato peel for the reaction of waste cooking oil. The catalyst was found to be rich in Ca, K, Mg, Si, and Na showing good catalytic activity at ORCs of 3 wt.% of the catalyst loading and 9:1 MTOR at 60°C temperature resulting in the biodiesel yield of 97.50%. Similarly, sweet potato leaves were reported as a catalyst source by Eldiehy et al. [162] for *Scenedesmus obliquus* oil as well as waste cooking oil biodiesel production. The ORCs for *Scenedesmus obliquus* oil were found to be 7 wt.% of the catalyst loading and 15:1 MTOR at a 60°C reaction temperature yielding 99.50% of biodiesel in 90 min. In the case of waste cooking oil, 5 wt.% of the catalyst loading and 9:1 MTOR at 60°C produced 98.0% of biodiesel in 120 min. Miladinović et al. [190] explored the catalytic activity of a solid catalyst prepared from hazelnut shell ash in the reaction of used cooking oil. They prepared the catalyst by burning the shell to bio-char and then subjecting the material to calcination at 800°C. The EDX analysis of the calcined catalyst revealed the presence of K (26.29%), Ca (11.62%), and Mg (6.77%) as abundant elements responsible for catalytic activity. The biodiesel yield of 98% was attained at the catalyst loading of 5 wt.% and MTOR of 12:1 at 60°C in a reaction time of 10 min. Sitepu et al. [191] reported the successful application of the catalyst prepared from palm bunch in the homogenizer-intensified biodiesel production from palm oil. With MTOR of 15:1, rotational speed of 4000 rpm, and 18 wt.% of the catalyst in a reaction time of 10 min, the highest biodiesel yield of 98.9% was achieved. They also stated that this method could save 67-87% of the reaction time and 6-98% of electricity. In addition to the applications of agricultural waste plant ashes, thermal power plant fly ash [192], coal fly ash [193, 194], and tar

and alkali ashes [195] have been described as solid catalysts for the synthesis of biodiesel.

**2.4. Biodiesel Properties.** The transformation of oil to biodiesel resulted in a decrease in density and viscosity with a moderate increase in the volatility of oil, which makes the properties of biodiesel similar to petrodiesel [10, 31, 196]. Density (15°C,  $\text{g cm}^{-3}$ ), kinematic viscosity (40°C,  $\text{mm}^2 \text{s}^{-1}$ ), cetane number, CFPP (°C), pour point (°C), flash point (°C), cloud point (°C), calorific value, etc., are some of the parameters to evaluate the quality of biodiesel. It is a prerequisite that the properties of the produced biodiesel must meet the specification recommended by ASTM-D6751, EN-14214, and other standards before being used as fuel. The properties of some biodiesels produced using the waste plant-derived heterogeneous base catalysts from varied feedstocks are depicted in Table 3. This reveals that the properties of the generated biodiesel are within the range of standards specified by EN-14214 and ASTM-D6751. The density and viscosity of the reported biodiesels are found to be well comparable with one another as well as are within the range of international standards except for the value reported by Chouhan and Sarma [113] ( $6.80 \text{ mm}^2 \text{ s}^{-1}$ ) for *Jatropha* biodiesel. A high cetane number is desirable for biodiesel to consider the ignition quality as a good fuel, and a higher value indicates higher combustion efficiency [197, 198]. Table 3 also reflects that the cetane number of the reported biodiesels is well above the minimum limit detailed in EN-14214 and ASTM-D6751, which signifies the compatible efficiency of the biodiesels. The higher heating value (calorific value) of the reported biodiesel showed variation from the higher to the lower value that measures the energy content of the fuel indicating the amount of energy produced when the biodiesel burns completely [199]. It is reported that, with an increase in the alkyl chain length and molecular weight, the calorific value increases, and with an increasing degree of unsaturation, it decreases [200, 201]. Conclusively, the properties of the synthesized biodiesel were found to meet the specification of international standards, and waste plant-derived heterogeneous base catalysts are efficient enough in producing quality biodiesels.

### 3. Comparison of the Reported Catalysts

Table 2 shows variations in catalytic activities of different agricultural waste-derived catalysts in the synthesis of biodiesel from various feedstocks. With a low catalyst amount of 0.5 wt.%, the plantain peel catalyst produced 97.96% of biodiesel at 45°C in 45 min [185]. A low concentration of 0.65% of the catalyst derived from cocoa pod husk [114] and *Musa paradisiaca* peel [106] also resulted in 99.3% of biodiesel at 65°C in 57 min. The activities of these two catalysts [106] seem to be lower compared to that of the plantain peel catalyst [185]. The elemental composition of the plantain peel catalyst [185] reveals the presence of a good amount of potassium (45.16%) along with oxygen (35.34%) depicting the presence of high potassium carbonate and, accordingly, exhibiting an efficient catalytic activity in transesterification (Tables 1 and 2). The reported FT-IR and XRD studies also portray the presence of potassium in the form of carbonate supporting the efficiency

TABLE 3: Comparison of properties of biodiesel produced using various heterogeneous base catalysts derived from agro-wastes.

Biodiesel feedstocks	Density (15°C, g/cm <sup>3</sup> )	Viscosity (40°C, mm <sup>2</sup> /s)	Cetane number	Properties						References
				PP (°C)	FP (°C)	CP (°C)	AV (mg of KOH/g)	IV (g I <sub>2</sub> /100 g)	CV (kJ/g)	
<i>Thevetia peruviana</i>	0.875	4.33	61.5	+3	+75	+12	0.057	69.9	44.986	[11]
<i>Jatropha curcas</i>	—	4.07	—	—	—	—	0.00	109	—	[99]
<i>Jatropha curcas</i>	0.875	5.7	48.6	+3	110	—	4.0	119.0	39.25	[110]
<i>Mesua ferrea</i>	0.890	5.525	—	—	113	—	1.8	113.2	35	[109]
Waste cooking oil	0.89	3.12	55	-9	145	-4	0.08	—	40.20	[108]
<i>Thevetia peruviana</i>	0.887	6.0	123	+1	196	+8	0.46	90.23	—	[111]
<i>Azadirachta indica</i>	0.88	5.0	81	9	274	21	0.45	58.6	48.7	[106]
<i>Bauhinia monandra</i>	0.876	4.90	59.83	+0	285	+20	0.45	52.22	43.19	[104]
Palm oil	0.86	4.3	76.93	-6	284	+3	0.4	40.90	—	[105]
<i>Jatropha curcas</i>	0.891	6.80	—	—	108	—	0.00	—	37.100	[113]
<i>Jatropha curcas</i>	—	4.21	57.1	—	164	—	0.05	—	—	[142]
<i>Azadirachta indica</i>	0.887	5.3	83	-10	262	23	0.5	58.96	45.88	[114]
Palm kernel oil	0.87	4.7	44.4	-3	300	+12	0.5	24.7	—	[105]
<i>Jatropha curcas</i>	0.875	4.75	48.3	-6	112	—	4.6	74.5	38.35	[209]
Soybean oil	0.888	4.9	52	+0	200	—	—	115.5	—	[210]
ASTM-D6751 standard	—	1.9–6.0	47 (min)	—	130 (min)	—	0.50 (max)	NS	—	—
EN-14214 standard	0.86–0.90	3.5–5.0	51 (min)	—	120 (min)	—	0.50 (max)	120 (max)	—	—

PP: pour point; FP: flash point; CP: cloud point; AV: acid value; IV: iodine value; CV: calorific value; min: minimum; max: maximum.

in the catalytic activity of the catalyst. Table 1 shows the presence of a very good amount of potassium in cocoa pod husk (59.2%) [114] and in *Musa paradisiaca* peel (51.02%) [106], which are comparatively higher than that in the plantain peel catalyst [185]. Despite having more potassium, the reported activities of these two catalysts are inferior compared to that of the plantain peel catalyst [185], which may be due to the presence of a lesser amount of potassium in the form of carbonate in these catalysts. The low amount of potassium as carbonate in the *Musa paradisiaca* peel [106] catalyst may be the reason for the lower catalytic activity compared to the plantain peel catalyst [185]. With a slightly higher catalyst loading of 1.5%, the catalyst derived from the mixture of kola nut, cocoa, and pumpkin waste [186] completed the transesterification in 40 min at a 55°C reaction temperature. With a similar catalyst loading of 1.5%, the *Musa acuminata* peel [188] completed the transesterification in 120 min at 60°C (Table 2). The comparatively less efficiency in the catalytic activity of the *Musa acuminata* peel [188] may also be due to the lower potassium content in the form of carbonate in comparison to the catalyst derived from the mixture of cocoa, kola nut, and pumpkin waste [186]. Thus, it can be clearly stated from Tables 1 and 2 that the presence of a good concentration of K in the form of carbonate or oxide in the catalysts produced from agro-wastes is the main constituent for the effective catalyst in the base-catalyzed biodiesel production. One additional aspect for the activity of the solid catalyst is its reusability and leaching. Catalyst reusability is a very important parameter as it can sig-

nificantly reduce the cost of the catalyst. If a solid catalyst can be reused multiple times without losing effectiveness, the overall process cost will be lowered. Reusability can also have environmental benefits by reducing the waste generation. Catalyst leaching is important because metal ions that leach from the solid catalyst can contaminate the reaction medium and reduce the yield of the product. Leached metal ions can also pose environmental hazards. There are many factors that influence the reusability of a solid catalyst and leaching, including the reaction conditions, catalyst type, and handling of the catalyst. All these factors have an influential role for selecting a suitable solid catalyst for an application.

#### 4. VIKOR Method-Based Ranking Study of Biodiesel Synthesis Catalyzed Using Agricultural Waste-Derived Heterogeneous Catalyst

The multicriterion decision-making VIKOR methodology is a multicriterion optimization and compromise solution [125]. The method is based on ranking and selecting from a set of alternatives under consistent criteria [122]. On the basis of negotiations, the compromised solutions could be obtained, involving the preference of decision makers via criterion weight [122]. The steps undertaken in the VIKOR strategy in the present study are mentioned below.

4.1. *Steps of VIKOR.* The steps of the VIKOR strategy are listed as follows:

*Step 1.* Establishment of a matrix of criteria and different alternatives.

*Step 2.* Normalization of the decision matrix.

*Step 3.* Calculation of the weight of the normalized decision matrix.

*Step 4.* Determination of the ideal solutions and nadir solutions (negative ideal solution).

*Step 5.* Computation of the distance for each alternative.

*Step 6.* Calculation of the relative closeness to the ideal solution.

*Step 7.* Rank of the preference order.

4.2. *Explanation of the Steps.* The steps are explained as follows:

*Step 1.* Determination of best and worst values:

$$\begin{aligned} f_i^+ &= \text{Max}(f_{ij}), \\ f_i^- &= \text{Min}(f_{ij}). \end{aligned} \quad (1)$$

*Step 2.* Normalization of  $S_j$  and  $R_j$ :

$$\begin{aligned} S_j &= \sum \left[ \frac{w_i(f_i^+ - f_{ij})}{f_i^+ - f_j^-} \right], \\ R_j &= \text{Max} \left[ \frac{w_i(f_i^+ - f_{ij})}{f_i^+ - f_j^-} \right]. \end{aligned} \quad (2)$$

*Step 3.* Computation of  $Q_j$  for group utility function:

$$Q_j = \frac{\nu(S_j - S^+)}{(S^+ - S^-)} + (1 - \nu) \left( \frac{R_j - R^+}{R^- - R^+} \right). \quad (3)$$

*Step 4.* Ranking the alternative

Sorting of  $R_j$ ,  $S_j$ , and  $Q_j$  are made from their minimum value. Hence, the three ranking lists are obtained.

*Step 5.* Acceptance of rank choice

*Case 1.*  $Q(a(2)) - Q(a(1)) \geq D_Q$ .

*Case 2.* Choice of random acceptance stability, where  $Q_j$  is the best choice from  $S$  and or  $R$  with  $\nu \geq 0.5$ .

Acceptance of rank choice:

C1: acceptance advantages:

$$(Q(a(2)) - Q(a(1))) \geq D_Q, \text{ where } D_Q = \frac{1}{j-1}, \quad (4)$$

where  $j$  is the number of alternatives.

C2: acceptance stability in decision-making. Alternatives must also be the best ranked by either the  $R$  value or  $S$  values.

4.3. *Conditions.* If any one of the conditions is not satisfied, then a set of compromise solutions will be proposed, and that consists of the following:

- (1) Alternatives  $a_1$  and  $a_2$ , if condition  $A_Q$  is not satisfied
- (2) Alternatives  $a_1, a_2, \dots, a_m$  if condition C1 is not satisfied  $a(m)$  are determined by the relation  $Q(a_m) - Q_1 < D_Q$  for maximum  $M$  (the position of these alternatives in closeness).

4.4. *Ranking Study.* The various factors governing the optimum reaction conditions (ORCs) for the cost-effective biodiesel production are the minimum or low catalyst concentration (wt.%), low MTOR, low reaction temperature, and short reaction time as well as high biodiesel yield (%). Considering the ORCs of the reported works (Table 2), a ranking study was performed for deliberation of the best catalyst in order of performance for probable recommendation in the large-scale biodiesel production and is the most necessary. The ranking study following the VIKOR method was conducted strictly on the basis of the parameters, viz., catalyst concentration ( $C_1$ ), MTOR ( $C_2$ ), reaction temperature ( $C_3$ ), reaction time ( $C_4$ ), and biodiesel yield ( $C_5$ ) (Table 2). The parameters are considered good if  $C_1, C_2, C_3,$  and  $C_4$  are low or minimum and if  $C_5$  is high or maximum. The result of the ranking study of the agricultural-waste-plant-based heterogeneous catalysts is portrayed in Table 4. Table 4 reveals that the catalyst prepared from plantain peel ( $A_{32}$ ) [185] utilized in the transesterification of waste cooking oil to biodiesel is showing the best performance and ranked first among the reported ones. This catalyst could complete the reaction with a minimum catalyst loading of 0.5 wt.%, lower MTOR (6:1), low reaction temperature (45°C), and short reaction time (45 min) producing a high biodiesel yield (97.96%). This plantain peel catalyst is followed by cocoa pod husk ( $A_{11}$ ) [114] and *Musa paradisiaca* peel ( $A_{12}$ ) [106] catalysts which are ranked second in the study. As discussed earlier, the presence of a good amount of potassium in the form of carbonate or oxide may be the key factor in the efficient catalytic activity of the plantain peel catalyst [185] compared to cocoa pod husk [114] and *Musa paradisiaca* peel [106] catalysts. With 4 wt.% of the catalyst loading and 3:2.4 MTOR at 65°C, the cocoa pod husk catalyst ( $A_{14}$ ) [105] converted palm kernel oil to biodiesel (100%) in 65 min and is ranked the third. Under identical ORCs and time, the banana fruit peel ( $A_{13}$ ) [105] could convert the oil to 99.96% biodiesel and is found in fourth rank. In this study, the lowest rank was shown to be the *Musa balbisiana* trunk ash catalyst [11]. This catalyst with 20 wt.% of the catalyst

TABLE 4: VIKOR method-based ranking study of reported agricultural waste-derived heterogeneous catalyst in biodiesel production.

Agricultural waste-derived catalyst/biodiesel feedstock	Catalyst load (wt.%)			Temp (°C)	Time (min)	Biodiesel (%)	$S_j$	$R_j$	$Q_j$	Rank
	$C_1$	$C_2$	$C_3$							
Coconut husk/Jatropha oil	A <sub>1</sub>	5	12	45	60	99.77	0.151972598	0.055483871	0.197970744	13
<i>Musa balbisiana</i> trunk/ <i>Thevetia peruviana</i> oil	A <sub>2</sub>	20	20	32	180	96	0.443941473	0.2	1	47
<i>Acacia nilotica</i> tree stem/ <i>Jatropha curcas</i> oil	A <sub>3</sub>	5	12	65	180	98	0.262324325	0.117525773	0.52227511	35
<i>Lemna perpusilla</i> Torrey/ <i>Jatropha curcas</i> oil	A <sub>4</sub>	5	9	65	300	89.43	0.385882337	0.2	0.922500043	45
<i>Musa balbisiana</i> underground stem/ <i>Jatropha curcas</i> oil	A <sub>5</sub>	5	9	275	60	98	0.3344406713	0.2	0.853788055	42
<i>Musa balbisiana</i> underground stem/ <i>Mesua ferrea</i> oil	A <sub>6</sub>	5	9	275	60	95	0.354208693	0.2	0.880220632	43
<i>Musa paradisiaca</i> peels/ <i>Thevetia peruviana</i> oil	A <sub>7</sub>	3	10	60	90	95.25	0.183736486	0.055670103	0.240901926	16
Banana ( <i>Musa Gros Michel</i> ) peels/ <i>Bauhinia monandra</i> oil	A <sub>8</sub>	2.75	7.6	65	69	98.5	0.136948734	0.041237113	0.137271052	7
Birch bark/palm oil	A <sub>9</sub>	3	12	60	180	69.7	0.424561601	0.2	0.974130871	46
<i>Musa balbisiana</i> peels/waste cooking oil	A <sub>10</sub>	2	6	60	180	100	0.183337449	0.117525773	0.416839861	31
Cocoa pod husk/ <i>Azadirachta indica</i> oil	A <sub>11</sub>	0.65	1.3	65	57	99.3	0.069366193	0.032989691	0.023529412	2
<i>Musa paradisiaca</i> peels/ <i>Azadirachta indica</i> oil	A <sub>12</sub>	0.65	1.3	65	57	99.3	0.069366193	0.032989691	0.023529412	2
Banana fruit peels/palm kernel oil	A <sub>13</sub>	4	1.25	65	65	99.96	0.104608949	0.038487973	0.086259309	4
Cocoa pod husk/palm kernel oil	A <sub>14</sub>	4	1.25	65	65	100	0.104344923	0.038487973	0.085906874	3
<i>Tamarindus indica</i> fruit peel/ <i>Parinari curatellifolia</i> oil	A <sub>15</sub>	5	9	60	120	96.2	0.213435945	0.07628866	0.339369635	29
Walnut shell/sunflower oil	A <sub>16</sub>	5	12	60	10	98	0.141437254	0.055483871	0.183907691	12
<i>Carica papaya</i> peel/ <i>Moringa oleifera</i> oil	A <sub>17</sub>	3.5	9	35	40	96.43	0.121307445	0.04	0.1112862941	5
Moringa leaves/soybean oil	A <sub>18</sub>	6	6	65	120	86.7	0.274963338	0.087788779	0.454308341	33
Cocoa pod husk + plantain peel/honne oil	A <sub>19</sub>	4.5	15	65	150	98.98	0.245592787	0.096907216	0.441117569	32
Ginger leaves/sunflower oil	A <sub>20</sub>	1.6	6	60	90	90.13	0.182527729	0.065148515	0.266329774	21
Spent coffee/palm oil	A <sub>21</sub>	4.94	6.68	65	82.42	97.08	0.173258191	0.050460481	0.212052279	14
<i>Mangifera indica</i> peel/soybean oil	A <sub>22</sub>	6	6	28	240	98	0.252890592	0.158762887	0.627329597	40
Pineapple leaves/refined soybean oil	A <sub>23</sub>	4	40	60	30	98	0.289442677	0.2	0.793768029	41
<i>Musa sapientum</i> peel/palm oil	A <sub>24</sub>	4	15	65	120	99.16	0.218657906	0.07628866	0.346340144	30
Kola nut pod husk/ <i>Hevea brasiliensis</i> oil	A <sub>25</sub>	3.5	6	65	75	96.77	0.151925831	0.045360825	0.169027862	11
Wheat straw/sunflower oil	A <sub>26</sub>	11.6	18.3	60.3	124	98.6	0.316278725	0.113846154	0.583798143	38
Acai seed/soybean oil	A <sub>27</sub>	12	18	100	60	98.5	0.307652462	0.117948718	0.583987792	39
Sugarcane bagasse/waste cooking oil	A <sub>28</sub>	5	15	60	15	92.12	0.199169432	0.070967742	0.305145783	26
Banana pseudostem/ <i>Madhuca indica</i> oil	A <sub>29</sub>	5.9	14.9	60	178.1	98.8	0.275887883	0.116219931	0.53665487	36
Wheat bran/waste cooking oil	A <sub>30</sub>	11.66	1.46	54.6	114.21	93.6	0.251637374	0.114461538	0.499267604	34
<i>Musa acuminata</i> flower petal/waste cooking oil	A <sub>31</sub>	5.63	6.24	28	221	99.99	0.224140697	0.145704467	0.551698037	37
Plantain peel/waste cooking oil	A <sub>32</sub>	0.5	6	45	45	97.96	0.076488926	0.024742268	0.009507745	1
Cocoa + kola nut + pumpkin/yellow oleander + rubber oil	A <sub>33</sub>	1.5	9	55	40	95.02	0.126295887	0.04	0.1119521739	6
	A <sub>34</sub>	3.53	9	90	80	96.63	0.192320828	0.050202429	0.236761741	15

TABLE 4: Continued.

Agricultural waste-derived catalyst/biodiesel feedstock	Catalyst load (wt.%)		Temp (°C)	Time (min)	Biodiesel (%)	$S_j$	$R_j$	$Q_j$	Rank	
	$C_1$	$C_2$								$C_3$
<i>Musa acuminata</i> and <i>Citrullus/Luffa cylindrica</i> , <i>Datura stramonium</i> , and <i>Lagenaria siceraria</i> oils										
Hazelnut shell/waste cooking oil	A <sub>35</sub>	5	12	60	10	98	0.141437254	0.055483871	0.183907691	12
Potato peel/waste cooking oil	A <sub>36</sub>	3	9	60	120	97.5	0.184342267	0.07628866	0.300534079	24
<i>Musa acuminata</i> peel/waste cooking oil	A <sub>37</sub>	1.5	9	60	120	98	0.165657321	0.07628866	0.27559257	23
Sweet potato leaves/microalgal oil	A <sub>38</sub>	7	15	60	90	99.5	0.222515773	0.070967742	0.336309533	28
Sweet potato leaves/waste cooking oil	A <sub>39</sub>	5	9	60	120	98	0.201554757	0.07628866	0.323510089	27
<i>Musa paradisiaca</i> peel/jatropha oil	A <sub>40</sub>	5	9	65	12	97.56	0.134280827	0.046153846	0.147736957	9
<i>Musa paradisiaca</i> trunk/jatropha oil	A <sub>41</sub>	5	9	65	9	97.65	0.131624911	0.046153846	0.144191722	8
<i>Musa paradisiaca</i> rhizome/jatropha oil	A <sub>42</sub>	5	9	65	14	95.67	0.148130645	0.046153846	0.16622432	10
Sugarcane bagasse/jatropha oil	A <sub>43</sub>	10	9	65	285	92.84	0.404346859	0.189690722	0.917735556	44
<i>H. fragrans</i> /jatropha oil	A <sub>44</sub>	7	12	65	65	97.75	0.205449509	0.066666667	0.301257999	25
<i>Sesamum indicum</i> /sunflower oil	A <sub>45</sub>	7	12	65	40	98.9	0.18067662	0.066666667	0.268190028	22
<i>Brassica nigra</i> /soybean oil	A <sub>46</sub>	7	12	65	25	98.79	0.171093414	0.066666667	0.255397932	17
<i>Brassica nigra</i> /soybean oil	A <sub>47</sub>	7	12	32	75	98.87	0.178208975	0.066666667	0.264896103	20
<i>Brassica nigra</i> /jatropha oil	A <sub>48</sub>	7	12	65	30	98.26	0.17802819	0.066666667	0.264654784	19
<i>Brassica nigra</i> / <i>Thevetia peruviana</i> oil	A <sub>49</sub>	7	12	65	25	97.78	0.177760081	0.066666667	0.2642969	18
Best ( $f_i^+$ )		0.5	1.25	28	9	100	$S^+, R^+$	0.069366193	0.024742268	
Worst ( $f_i^-$ )		20	40	275	300	69.7	$S, R$	0.443941473	0.2	

loading and 20:1 MTOR at 32°C yielded 96% biodiesel in 180 min of the reaction time and was found to be in the 47th rank (Table 4). The present study successfully demonstrates the ranking of catalysts prepared from various plant ashes reported in biodiesel synthesis. Considering variability in the composition of different plant species and among the same species as listed in Table 1, the ranking study among the catalysts reported in biodiesel synthesis is ambiguous. However, the present study can successfully be applied for ranking amongst the reported catalysts for decision-making, and ranking was conducted strictly on the basis of reported reaction conditions (Table 2) but not on the basis of ash composition. One more important aspect for solid catalyst selection is the catalyst reusability and leaching of active components of the catalyst. However, the catalyst reusability and leaching were also not investigated in this ranking study. Conclusively, by considering more variables, the ranking study using the VIKOR multicriterion method for catalysts obtained from different plant ash materials can be undertaken to overcome the constraints. This ranking study of the catalytic performance via the VIKOR method discloses that all the criteria considered are contributing to the rank of the catalyst. This method is useful in comparing the huge amount of data where manual comparison is not possible, and the data can be ranked easily by following this method.

## 5. Conclusions

Biodiesel, the emerging alternative to petrodiesel, is reported to be synthesized typically from triglyceride sources via catalytic transesterification, wherein the agricultural waste-derived heterogeneous catalysts are endorsed as one of the most promising, cost-effective, and green protocol solutions. The cost-effectiveness of the produced biodiesel is influenced by various parameters such as oil feedstock, reactor used, type of catalyst, catalyst concentration, MTOR, reaction time, reaction temperature, and biodiesel yield. In this study, the ranking study using the VIKOR method was performed to identify the potential catalysts in terms of their performance among the selected agricultural waste-derived catalysts that were reported for biodiesel production. On the basis of the parameters selected ( $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$ , and  $C_5$ ), this study listed the plantain peel catalyst in the first rank followed by *Musa paradisiaca* peel and cocoa pod husk catalysts in the second rank. Thus, the VIKOR method can be a useful tool for comparison and ranking purposes if there are a large number of data, and this may be expanded for thorough study by considering more criteria which may give more fruitful results.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Biswajit Nath was responsible for the methodology, investigation, and writing of the original draft. Bhimraj Basumatary was responsible for the conceptualization, validation, and data analysis. Nijwm Wary was responsible for the validation and data analysis. Usha Rani Basumatary was responsible for the validation and data analysis. Jili Basumatary was responsible for the validation and data analysis. Samuel Lalthazuala Rokhum was responsible for the validation and review and editing of the manuscript. Mohammad Azam was responsible for the validation and review and editing of the manuscript. Kim Min was responsible for the validation and review and editing of the manuscript. Sanjay Basumatary was responsible for the conceptualization, supervision, and review and editing of the manuscript.

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