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Synthesis and Characterization of Potent Catalysts for Production of Biokerosene

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Abstract

The increasing demand for sustainable aviation fuels has stimulated interest in the development of low-cost and environmentally friendly catalysts derived from renewable waste resources. This study investigates the synthesis and physicochemical characterization of heterogeneous catalysts produced from two abundant agricultural waste materials, rice husk and eggshell, for potential application in the catalytic upgrading of bio-oil to bio-kerosene. Rice husk and eggshell samples were collected locally and subjected to a series of pre-treatment processes, including washing, drying, grinding, and calcination, to produce silica (SiO_2) and calcium oxide (CaO)-based catalysts, respectively. Comprehensive catalyst characterization was carried out using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Fluorescence (XRF), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), and Brunauer–Emmett–Teller (BET) surface area analysis. BET results revealed that the rice husk-derived catalyst possessed a specific surface area of 282.1 $m^2\ g^{-1}$, whereas the eggshell-derived catalyst exhibited a significantly higher surface area of 726.2 $m^2\ g^{-1}$. Both catalysts displayed mesoporous pore structures, indicating favourable textural properties for catalytic applications involving large organic molecules. FTIR analysis identified characteristic absorption bands at approximately 3000 cm^{-1}, 1050–1100 cm^{-1}, and 2800–2950 cm^{-1}, corresponding to O–H stretching vibrations associated with adsorbed moisture, Si–O–Si vibrations characteristic of silica, and C–H vibrations associated with calcium oxide-based materials, respectively. XRF analysis confirmed the dominance of silica (86.6 wt.%) in the rice husk catalyst and calcium oxide (89 wt.%) in the eggshell catalyst. XRD patterns revealed the presence of both crystalline and amorphous phases, while TGA results demonstrated excellent thermal stability for both catalysts beyond 500°C. The study therefore confirms the successful synthesis of highly active and thermally stable heterogeneous catalysts from rice husk and eggshell wastes, highlighting their potential application in the conversion and upgrading of bio-oil into bio-kerosene and other sustainable biofuels.

Keywords
Synthesis,
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Eggshell,
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1.0 INTRODUCTION

Bio-kerosene (jet fuel) is a form of biofuel that can serve as a direct substitute for aviation kerosene from fossil fuels, and can be produced by hydro-treating bio-oils from plants, animal fats, or other forms of biomass feed stocks (Ekpenkhio, 2024). Bio kerosene possesses comparable fuel properties to the conventional kerosene but offers a number of ecofriendly benefits, including lower emission of oxides of carbon, nitrogen, and sulfur (COx, NOx and SOx), thereby, minimizing emissions of greenhouse gases (Kumar *et al.*, 2012; Selvam *et al.,* 2025).

Over the past years, catalytic upgrading of bio-fuels has gain prominence among researchers due to its potential to improve the quality, and yield of the bio-oil production process. Catalyst plays an important role in the different bio-fuel upgrading processes such as hydro treating, cracking and trans-esterification (Zhao *et al.*, 2017; Kundu *et al.*, 2024).

The most widely used heterogeneous catalysts in bio-oil upgrading are metals and their oxides due to their high stability, activity, selectivity and recyclable nature. Notable examples of heterogeneous catalysts active metals and support reportedly used for bio-fuel upgrading includes Ni, Pd, Pt, Biochar, carbon nanotubes etc (Nguyen *et al.*, 2016; Cheng *et al.*, 2018; Carrasco *et al.*, 2024). These catalysts have been reported to improve the yield of biodiesel from triglycerides, improve quality of bio-oil, and increase fuel stability. Several researches have explored the use of different heterogeneous catalysts for bio-oil upgrading, and these include supported metals, metal oxides and zeolites (Wang *et al.*, 2012). These solid catalysts have been reportedly used for hydrodeoxygenation, trans-esterification and catalytic cracking reactions. Metal oxides, such as ZnO, MgO, and CaO have been extensively studied for trans-esterification reactions. For example, ZnO has been shown to have high catalyst activity of over 90% for biodiesel production from vegetable oils (Mazaheri *et al.*, 2021; Farouk *et al.*, 2024).

Supported metal catalysts, such as Ni/SiO_2, Ni/biochar and Pd/C, have been used for hydro-deoxygenation reactions. These catalysts have shown significant improvements with promising performance for bio-oils upgrading in terms of yield and fuel quality (Yusuf, 2024; Mudi *et al.*, 2023). In spite of the huge benefits offered by heterogeneous catalysts in bio-fuel upgrading, some impending challenges such as cost and catalyst stability remain to be addressed. Additional study is required to develop a more effective and low-cost catalyst that can be incorporated into the current processes and infrastructure. The use of agricultural wastes such as rice husk and egg shell offer a cheaper and renewable and environmentally friendly alternative source of heterogeneous catalysts for bio-oil upgrading due to their low cost, availability, and biodegradable nature.

Rice husk is considered a waste with high resistance to decomposition and has a low nutritional value to animals and also being difficult to digest. Rice husks also have low calorific value (3585 kcal kg^{-1}) and high ash content when burnt (Ameri *et al.,* 2019; Tsai *et al.*, 2025). The ash contains nearly 95% silica and is an important renewable source of silica. In addition, the ash contains potassium, sodium, magnesium, calcium, iron, phosphorus and much smaller quantities of other elements

(Hamidu *et al.*, 2025). The physical and chemical characterization of the rice husk plays a vital role in determining the feasible process for effective utilization of rice husk (Shen, 2017; Wazir *et al.*, 2024). The reactivity of rice husk ash is based on the properties of amorphous silica and the porous structure of ash (Ong *et al.,* 2019). Amorphous silica is obtained between temperatures of 500-700°C (Kang, 2019) and has a large specific area and the chaotic formation of the structure is open with holes in the network where electrical neutrality is not satisfied. Crystalline silica structure is formed by the repetition of a basic unit. The structure of crystalline silica reduces the surface area of RHA; thus, reduces its reactivity (Leong, 2015).

Egg shells are useful in the preparation of heterogeneous catalysts. Eggshell CaO is a promising green catalyst in biofuel production and has many bioactive compounds exhibiting high economic benefits (Birol 2019). Internationally, about 250,000 tons of eggshell waste is released annually (Faridi and Arabhosseini, 2018). Egg shells are agricultural bio-waste materials that are biodegradable, recyclable and biocompatible (Pedavoah , 2018). It is mainly composed of calcium carbonate ($CaCO_3$), which accounts for about 93.6% by weight, followed by calcium triphosphate (0.8%), which accounts for about 10% of an egg. The main component of eggshells is calcium carbonate, $CaCO_3$, which can be converted to calcium oxide and carbon dioxide when burnt. It is therefore an excellent biomass resource for synthesizing CaO catalyst (Faridi and Arabhosseini 2018; Makarevičienė *et al.*, 2025). Egg shell CaO has a specific surface area that is 1.54 times higher than commercially available calcium oxide (Bharti *et al.*, 2019; Prayitno *et al.*, 2025). It has a large specific surface area and high catalytic activities, making it an efficient catalyst for the production of biofuel with high yields (Santos, 2019; Prayitno *et al.*, 2025). This research aim to synthesis and characterize catalysts from rice husk and egg for bio kerosene production.

2.0 MATERIAL AND METHODS

The samples used in this research are rice husk and egg shell. The rice husk and egg shell were collected from a local rice mill factory located at Gidan Dare, Sokoto North and Local tea sellers (Mai Shayi), Usmanu Danfodiyo University minimart, Sokoto respectively. They were thoroughly washed and sun dried.

2.1 Catalyst preparation

The rice husk ash was prepared by open air burning to get the rice husk ash. To prepare the catalyst, silica from rice husk ash was treated by impregnation and calcination processes. The silica was mixed with 1M NaOH solutions with ratio 1:10. The mixture was heated at 100 °C for 1 h at a stirring speed of 350 rpm, filtered and dried at 110 °C. The silica was then calcined at 500 °C for 2 hours (Chia, 2022). CaO catalyst was prepared through the process of calcining the egg shell. The egg shell was washed thoroughly cleaned using tap water followed by rinsing with distilled water. The cleaned egg shell was dried in a hot oven at 105°C for 24 hours. Once dried, the egg shell was grinded into small particles and calcined in a muffle furnace with under air at 900°C for 2.5 hours (Odeh *et al* 2024). Both calcined rice husk and egg shell were stored in an air tight container for later use.

2.2. Catalyst characterization

a) Fourier Transform-Infra-Red (FT-IR) Analysis

The FT-IR analyses were carried out using the Center for Advanced Science Research and Analytical Services (CASRAS), Usmanu Danfodiyo University, Sokoto using an agilent Cary 630 FT-IR spectrometer with a base system of a high infrared radiation emission. The base is used in conjunction with 5-bounce diamond ATR sampling accessories of internal reflection element (IRE) crystal. The analysis was carried out in the transmittance mode and the signal collected within the range of 4000 – 650 cm^{-1} wave number. The sample scan was 32 while the background scan was also 32 and the resolution was set at 4. The generation of sample spectra was achieved through microla software.

b) X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses

The powdered X-ray Diffraction (PXRD) analysis was carried out using the Rigaku MiniFlex 6G equipped with the Rigaku SmartLab Software Situated at Central Advance Science Laboratory Complex (CASLAC), Usmanu Danfodiyo University, Sokoto. The measurement was done with Cu-Kα radiation (40Kv, 15mA) using a Sc-70 detector recorded over 3 – 90° 2 range at a speed of 10.00°/min. The basal spacing (d001) values were also determined from XRD patterns. The X-ray fluorescence (XRF) analyses were carried out using EDXRF analyzer at Advance Science Central Laboratory, Umaru Musa Yar'Adua University, Katsina.

c) Thermo-gravimetric analysis (TGA)

Thermo-gravimetric analysis is an analytical technique in which weight loss of the sample is measured with respect to time or temperature. In this study, it was used to examine the thermal stability of the rice husk and egg shell catalysts. A PerkinElmer TGA 800 equipment was used to carry out thermo-gravimetric analyses of the samples. About 17.5 mg of the catalyst was placed on the zeroed sample pan, nitrogen flow switched on and the sample loaded onto the furnace. Thermo-gravimetric analysis was performed on the catalysts under nitrogen atmosphere (purity 99.9%) and the temperature ramped from 25°C to 800°C at a rate of 10°C per minute. During TGA analyses, sample weight changes over the temperature range are continuously recorded as the gaseous products are removed.

d) Surface area and pore volume determination

The surface area, pore width and pore volume analyses of the prepared catalysts were determined using N_2 adsorption isotherms at 77.35K using Quantachrome Instrument (Version 11.03). The samples were degassed for 3 hours at 250°C in a vacuum. The surface area was was determined using multiple point Brunauer-Emmet-Teller (BET) method. The pore volume and pore size were estimated using Barrett-Joyner-Halenda (BJH) method (Brame et al., 2016).

3.0 RESULTS AND DISCUSSION

3.1 Catalyst Characterization

There is a strong connection between the structural features of heterogeneous catalysts and their catalytic performance. This stage of catalyst development uses physical and chemical methods to evaluate important catalytic properties of the catalysts and also provide a clear understanding of the relationship between catalyst structure and its performance. The obtained calcined rice husk and egg shell were analyzed using Brunauer-Emmett-Teller (BET) surface area, Thermo-gravimetric (TGA), X-ray Fluorescence Spectroscopy (XRF), Fourier Transform-infrared (FT-IR) spectroscopy and X-ray diffraction (XRD) analyses.

3.1.1 Surface area, pore sizes and pore volume

Three important properties of heterogeneous catalysts are the catalyst surface area, pore size and pore volume. The surface area, pore volume and pore size of the calcined rice husk and egg shell catalyst were determined using N_2 adsorption-desorption isotherms as shown in **Table 3.1**.

Table 3.1 Surface area, Pore diameter and Pore Volume

Catalyst	BET Surface area (m^2/g)	Pore Diameter (nm)	Pore Volume (cc/g)
Rice husk	282.091	2.442	0.171
Egg shell	726.198	2.453	0.384

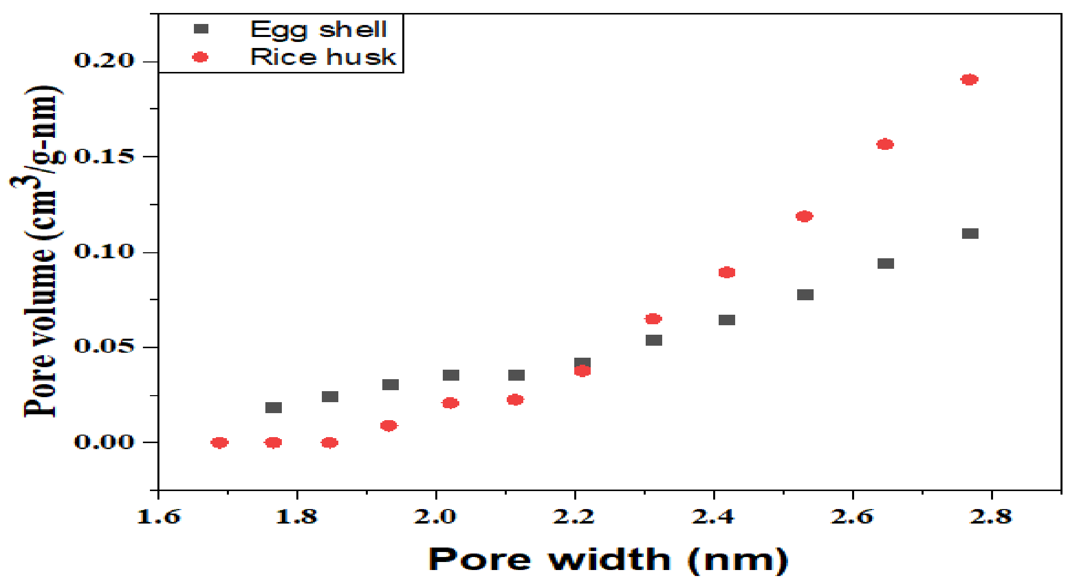

Figure 3.1: Pore size distribution of egg shell and rice husk catalysts

Table 3.1, revealed that the egg shell has a high BET surface area of 726.2 m^2/g, pore volume of 0.4 cc/g, and a pore diameter of 2.5 nm. The high surface area observed in egg shell catalyst suggests that the egg shell has a well-developed microporous to mesoporous sites (Figure 3.1) which provides it with the catalytic potential to effectively catalyze chemical reactions that requires a number of catalytic active sites (Zdravkov, 2007; Laca, 2017). Rice husk catalyst showed a lower surface area of 282.1 m^2/g, pore diameter of 2.4 nm, and a pore volume of 0.2 cc/ g. Though, rice husk has lower surface area, pore volume and pore diameter, the catalyst demonstrates a moderate surface area and porosity which can favor adsorption and catalytic applications.

The pore size distribution of both egg shell and rice husk catalysts falls within microporous (<2nm) and mesoporous (2nm-50nm) pore diameter (Zdravkov, 2007) (Figure 3.1) which can facilitate the diffusion of reactants and products into and out of the pores of the catalyst respectively during chemical reaction (Peng *et al*, 2020). The BET surface area, pore volume and pore diameter obtained for the synthesized catalysts are in consistent with and in some cases surpasses that of some previously reported catalysts for biokerosene production in literatures (Neuling and Kaltschmitt, 2015; Al-Muttaqii et al., 2019; Achinas *et al.*, 2021).

3.1.2 Thermo-gravimetric and Differential Analyses (TGA)

The thermal stability of the prepared catalysts was determined using TGA. This involves hating the catalysts at a constant rate of temperature rise. The catalyst response to temperature change in terms of weight loss was studied as shown in Figure 3.2 below.

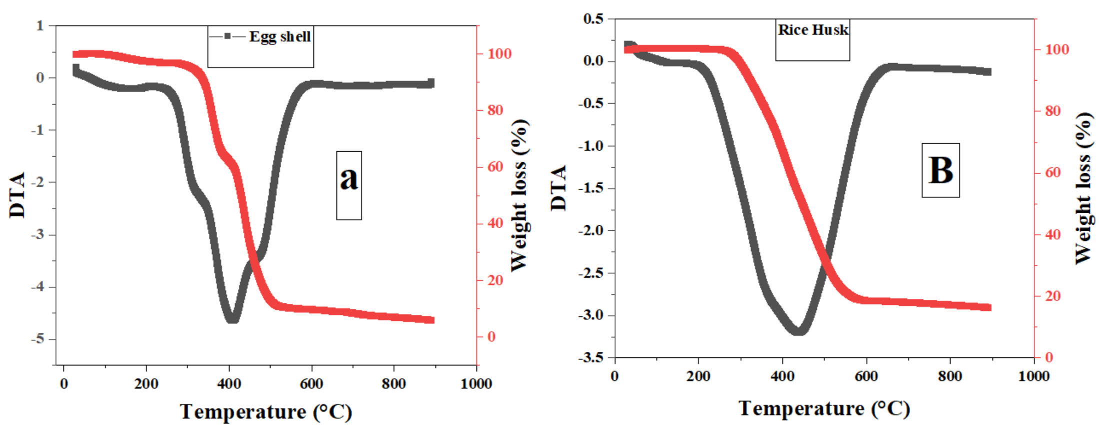

Figure 3.2: Thermo-gravimetric (TGA) and Differential Thermal Analysis (DTA) of a) Egg shell b) Rice Husk

The TGA profile (Figure 3.2) shows the thermal decomposition pattern and stability of the egg shell and rice husk catalysts. The first thermal peaks for the catalysts occur between 29°C – 250°C with initial weight loss of 1-5% which could be attributed to loss of adsorbed moisture.

A significant weight loss of about 91% occurred between 250°C to 500°C in both the rice husk and egg shell catalysts. This could be attributed to the thermal decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and carbon (iv) oxide (CO_2) in egg shell catalyst (Razali , 2022) as confirmed by the XRF analyses in Table 3.1.

The prominent degradation (250°C-500°C) in rice husk corresponds to the thermal decomposition of organic matter such as lignin, cellulose, and hemicellulose. The silica content of the rice husk also contributed to high thermal stability in rice husk catalyst (Azmi, 2016). The two samples (egg shell and rice husk) both shows stable peaks with no significant weight loss beyond 500 °C, indicating high stability of the samples at higher temperatures >500 °C (Liou, 2004;

Razali, 2022). Similar catalyst stability was observed for some reported catalysts used for biokerosene production (de Sausa *et al.*, 2021; de Medeiros *et al.*, 2022)

3.3 X-Ray Fluorescence Spectroscopy

The mineral content and their percentage in the egg shell and rice husk catalysts were assessed using X-Ray Fluorescence Spectroscopy as shown in the Table 3.1.

Table 3.2 The mineral content in both egg shell and rice husk and their percentage

Sample	Mineral content	% Content
Egg shell	CaO	89
Rice husk	SiO_2	86.6

Table 3.2 revealed the mineral content in both rice husk and egg shell and their percentages. The results showed that the egg shell is very rich in calcium oxide (CaO) with about 89% CaO, obtained from the thermal decomposition of calcium carbonate ($CaCO_3$) which is in line with findings by Rohim (2014) as confirmed by the TGA analysis (Figure 3.2). The rice husk contained mainly SiO_2 of about 86%, a thermally stable mineral and this is also in agreement with findings by Adamu (2020). Calcium oxide and SiO_2 based catalysts have proven to be a reliable catalyst in bio-oil upgrading reactions reactions for biodiesel production in many literatures (Yi *et al.*, 2019; Yi *et al.*, 2020; Kotsur, 2022)

3.4 Fourier Transform-infrared (FT-IR) spectroscopy

The calcined egg shell and rice husk were analyzed using ft-ir to identify the absorption bands of functional group present. Figure 3.3a and 3.3b depict the ft-ir spectra of calcined egg shell and rice husk samples.

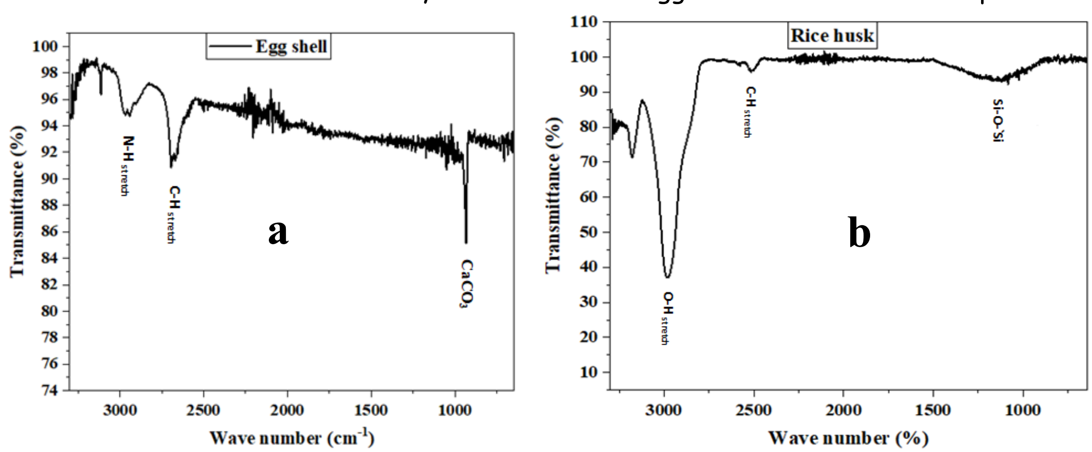

Figure 3.3: Fourier Transform-infrared (FT-IR) spectroscopy of a) Egg Shell catalyst and b) Rice Husk catalyst.

The ft-ir analyses of egg shell catalyst showed a peak for C-H stretching vibration between 2850 cm^{-1} – 2920cm^{-1} for lignin, cellulose, and hemicellulose (Fig. 3.3a) (Haddad *et al.*, 2021; Mohadi, 2016). A weak peak observed at 3000 cm^{-1} can be attributed to protein or amide group stretching vibration which indicate the presence of protein in the egg shell membrane (Fig. 3.3a) (Ajala 2018; Witoon, 2011). A strong peak observed between 870 cm^{-1} and 875 cm^{-1} was also observed and this is associated with calcium oxide (CaO) from calcium carbonate vibration ($CaCO_3$) (Fig. 3.3a) (Witoon, 2011) which is the main constituent of egg shell as confirmed by the x-ray fluorescence (XRF) analyses (89%) in Table 3.1.

The Ft-ir analyses of rice husk catalyst showed a broad peak around 3000 cm^{-1} for O-H stretching vibration of hydroxyl group from adsorb water (Fig. 3.3b) (Carmona, 2013). A C-H vibration was observed between 2800 cm^{-1} - 2950 cm^{-1} from residual organic matter and a strong peak was also observed between 1050 cm^{-1} - 1100 cm^{-1} for Si-O-Si (Silica) (Fig. 3.3b) (Armynah, 2018; Carmona, 2013) which is the main constituent of rice husk as confirmed by the x-ray fluorescence (XRF) analyses (86.6%) in Table 3.1. The Fi-ir analyses of egg shell confirm the presence of calcium oxide (CaO) with minimal organic matter (Fig 3.3a) while that of rice husk indicate the presence of a significant amount silica (SiO_2) (Fig. 3.3b).

3.5 X-ray Diffraction Spectroscopy (XRD) analyses

X-ray diffraction (XRD) is a rapid technique primarily used to examine the degree of crystallization, which are the size, composition and crystal structure of pure samples. Figure 3.4 shows the XRD diffractogram of the calcined egg shell and rice husk.

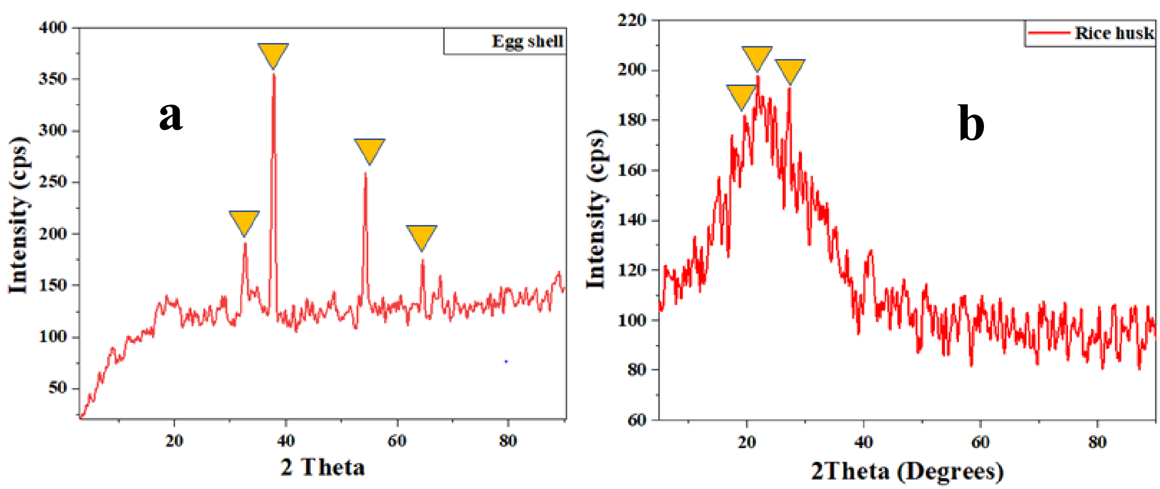

Figure 3.4:X-ray Diffraction Spectroscopy (XRD) analyses

The XRD analyses of egg shell showed a diffraction peak of the crystalline phase which is the main component of egg shell (Fig 3.4a). The main peaks were observed at 2θ values of 32.2° (111), 37.4° (200), 53.9° (22064.2° (311) and 67.4° (222), which are the characteristic peaks of calcium oxide obtained from the decomposition of calcium carbonate at high temperature of 700 °C – 800 °C (Naemchanthara, *et al.*, 2008; Park *et al.*, 2007).

The XRD of the rice husk catalyst revealed a broad peak at 2θ value of 22° for amorphous cellulose, peaks at 2θ =20-25, and 26.6 are for quartz (SiO_2) (Park, 2007; Mijan, 2014). This confirm that the rice husk catalyst mainly contains amorphous SiO_2. The XRD analyses of the synthesized catalyst showed that the egg shell is made of primarily calcium oxide as the mineral phase while the rice husk catalyst is made of mainly silica as the major component. Both CaO and Silica have proven good candidates for bio-oil upgrading reactions reported in the literature (Yi *et al.*, 2019; Zhang et al., 2024; Böhme *et al.*, 2025)

4.0 CONCLUSION

The conversion of agricultural waste such as rice husk and egg shell into catalyst for bio-kerosene production is a green strategy. The present work was designed to synthesize and characterize CaO and SiO_2 based heterogeneous catalyst from egg shell and rice husk. The characterizations conducted on the two catalysts reveal the feasibility of transforming agricultural wastes into valuable resources for green energy applications. Both rice husk and egg shell exhibited favourable chemical and structural properties vital for catalytic application in bio-kerosene production.

The CaO catalyst derived from egg-shell showed higher surface area, larger pore sizes, and better thermal stability, making it very suitable for hydrodeoxygenation and trans-esterification reactions. On the other hand, SiO_2 catalyst derived from rice husk, have a moderate surface area, amorphous structure, and offers potential as both catalyst and support material for bio-kerosene production. XRD, XRF, and FT-IR analyses confirmed the successful synthesis of calcium oxide (CaO) and Silica (SiO_2) phases, while TGA confirmed the catalysts stability at high temperatures, indicating durability during catalytic reactions.

These research findings support the use of low-cost renewable, agricultural wastes as alternate source for active heterogeneous catalyst development, contributing to green and sustainable bio-fuel production and proper waste management. The study offers a solid foundation for future research on optimization of catalyst synthesis parameters (impregnation method and calcination temperature) to enhance catalyst performance. This work is also in line with the on-going global fight against climate change, promoting circular economy by reducing the over-dependence on fossil fuel and the use of expensive catalysts for bio-fuel production.

REFERENCES

Achinas, S., Margry, S., & Euverink, G. J. W. (2021). A technological outlook of biokerosene production. In Sustainable Biofuels (pp. 225-246). Academic Press.

Adamu, G. D., Shuaibu, H. Y., Maharaz, M. N., Chifu, E. N., Silikwa, N. W., Lariski, F. M., ... & Benedict, J. N. (2020). Elemental analysis of rice husk using X-ray fluorescence techniques–a case study of Jigawa State, Nigeria. *Dutse Journal of Pure and Applied Sciences*, *7*(4b).

Ajala, E. O., Eletta, O. A. A., Ajala, M. A., & Oyeniyi, S. K. (2018). Characterization and evaluation of eggshell for use as a bio-resource. Arid Zone Journal of Engineering, Technology and Environment, 14(1), 26-40.

Al-Muttaqii, M., Kurniawansyah, F., Prajitno, D. H., & Roesyadi, A. (2019). Bio-kerosene and bio-gasoil from coconut oils via hydrocracking process over Ni-Fe/HZSM-5 catalyst. Bulletin of Chemical Reaction Engineering & Catalysis, 14(2), 309-319.

Ameri F, Shoaei P, Bahrami N, Vaezi M, Ozbakkaloglu T (2019). Optimum rice husk ash content and bacterial concentration in selfcompacting concrete. Construction and Building Materials 222:796813.

Armynah, B., Atika, Djafar, Z., Piarah, W. H., & Tahir, D. (2018, March). Analysis of chemical and physical properties of biochar from rice husk biomass. In Journal of Physics: Conference Series (Vol. 979, p. 012038). IOP Publishing.

Azmi, M. A., Ismail, N. A. A., Rizamarhaiza, M., K, W. H. A., & Taib, H. (2016, July). Characterisation of silica derived from rice husk (Muar, Johor, Malaysia) decomposition at different temperatures. In *AIP Conference Proceedings* (Vol. 1756, No. 1, p. 020005). AIP Publishing LLC.

Bakar RA, Yahya R, Gan SN (2016). Production of high purity amorphous silica from rice husk. Procedia Chemistry 19:189-195.

Bharti, P., Singh, B., & Dey, R. K. (2019). Process optimization of biodiesel production catalyzed by CaO nanocatalyst using response surface methodology. Journal of Nanostructure in Chemistry, 9(4), 269-280.

Böhme, M., Jensen, P. A., Høj, M., Hansen, B. B., Stummann, M. Z., & Jensen, A. D. (2025). Conversion of Furfural as a Bio-Oil Model Compound over Calcium-Based Materials as Sacrificial Low-Cost Catalysts for Bio-Oil Upgrading. Catalysts, 15(6), 554.

Brame, J. A., & Griggs, C. S. (2016). Surface area analysis using the Brunauer-Emmett-Teller (BET) method: scientific operation procedure series: SOP-C.

Carmona, V. B., Oliveira, R. M., Silva, W. T. L., Mattoso, L. H. C., & Marconcini, J. M. (2013). Nanosilica from rice husk: extraction and characterization. Industrial Crops and Products, 43, 291-296.

Carrasco Díaz, A., Abdelouahed, L., Brodu, N., Montes-Jiménez, V., & Taouk, B. (2024). Upgrading of pyrolysis bio-oil by catalytic hydrodeoxygenation, a review focused on catalysts, model molecules, deactivation, and reaction routes. Molecules, 29(18), 4325.

Cheng, S., Wei, L., Alsowij, M. R., Corbin, F., Julson, J., Boakye, E., & Raynie, D. (2018). In situ hydrodeoxygenation upgrading of pine sawdust bio-oil to hydrocarbon biofuel using Pd/C catalyst. *Journal of the Energy Institute*, *91*(2), 163-171.

De Medeiros, A. M., de Sousa Castro, K., de Macêdo, M. L. G., de Morais Araújo, A. M., da Silva, D. R., & Gondim, A. D.

(2022). Catalytic pyrolysis of coconut oil with Ni/SBA-15 for the production of bio jet fuel. Rsc Advances, 12(16), 10163-10176.

De Sousa Castro, K., de Medeiros Costa, L. F., Fernandes, V. J., de Oliveira Lima, R., de Morais Araújo, A. M., de Sant'Anna, M. C. S., & Gondim, A. D. (2021). Catalytic pyrolysis (Ni/Al-MCM-41) of palm (Elaeis guineensis) oil to obtain renewable hydrocarbons. RSC advances, 11(1), 555-564.

Ekpenkhio, J. E. (2024). Production of bio-kerosene from jatropha curcas seeds: evaluation and parameter influence. Current Journal of Applied Science and Technology, 43(5), 52-60.

Faridi, H., & Arabhosseini, A. (2018). Application of eggshell wastes as valuable and utilizable products: A review. *Research in Agricultural Engineering*, *64*(2).

Farouk, S. M., Tayeb, A. M., Osman, R. M., & Abdel-Hamid, S. M. (2024). Sustainable production of biodiesel from waste cooking oil using magnesium oxide nano catalyst: An optimization study. *Scientific Reports*, *14*(1), 22010.

Haddad, B., Mittal, A., Mittal, J., Paolone, A., Villemin, D., Debdab, M., ... & Belarbi, E. H. (2021). Synthesis and characterization of Egg shell (ES) and Egg shell with membrane (ESM) modified by ionic liquids. *Chemical Data Collections*, *33*, 100717.

Hamidu, I., Afotey, B., Kwakye-Awuah, B., & Anang, D. A. (2025). Synthesis of silica and silicon from rice husk feedstock: A review. Heliyon, 11(4).

Kang SH, Hong SG, Moon J (2019). The use of rice husk ash as reactive filler in ultra-high-performance concrete. Cement and Concrete Research 115:389-400.

Ko, C. H., Park, S. H., Jeon, J. K., Suh, D. J., Jeong, K. E., & Park, Y. K. (2012). Upgrading of biofuel by the catalytic deoxygenation of biomass. *Korean Journal of Chemical Engineering*, *29*(12), 1657-1665.

Kotsur, M. (2022). An Evaluation of Catalyst Applications in Bio-Oil Upgrading and Biomass Pyrolysis. Journal of Enterprise and Business Intelligence, 2(4), 235-246.

Kumar, S., Chaube, A., & Jain, S. K. (2012). Sustainability issues for promotion of Jatropha biodiesel in Indian scenario: a review. *Renewable and Sustainable Energy Reviews*, *16*(2), 1089-1098.

Laca, A., Laca, A., & Díaz, M. (2017). Eggshell waste as catalyst: A review. Journal of environmental management, 197, 351-359.

Leong TL (2015). Effects of Rice Husk Ash (RHS) Produced from Different Temperatures on the Performances of Concrete (Doctoral dissertation, UTAR). http://eprints.utar.edu.my/id/eprint/1751

Makarevičienė, V., Gaidė, I., & Sendžikienė, E. (2025). Heterogeneous Catalysts from Food Waste for Biodiesel Synthesis—A Comprehensive Review. Catalysts, 15(10), 957.

Mijan, M. A., Kim, D. H., & Kwak, H. S. (2014). Physicochemical properties of nanopowdered eggshell. International Journal of Food Science and Technology, 49(7), 1751-1757.

Mohadi, R., Anggraini, K., Riyanti, F., & Lesbani, A. (2016). Preparation calcium oxide from chicken eggshells. Sriwijaya Journal of Environment, 1(2), 32-35.

Mudi, I., Hart, A., Ingram, A., & Wood, J. (2023). Catalytic hydrodeoxygenation of vanillin, a bio-oil model compound over renewable Ni/biochar catalyst. *Catalysts*, *13*(1), 171.

Naemchanthara, K., Meejoo, S., Onreabroy, W., & Limsuwan, P. (2008). Temperature effect on chicken egg shell investigated by XRD, TGA and FTIR. Advanced Materials Research, 55, 333-336.

Neuling, U., & Kaltschmitt, M. (2015). Conversion routes for production of biokerosene—status and assessment. Biomass Conversion and Biorefinery, 5(4), 367-385.

Nguyen, H. K., Pham, V. V., & Do, H. T. (2016). Preparation of Ni/biochar catalyst for hydrotreating of bio-oil from microalgae biomass. *Catalysis Letters*, *146*(11), 2381-2391.

Ong HR, Iskandar WME, Khan MMR (2019). Rice Husk Nanosilica Preparation and Its Potential Application as Nanofluids. In Silver Nanoparticles-Health and Safety. IntechOpen DOI: 10.5772/intechopen.89904.

Park, H. J., Jeong, S. W., Yang, J. K., Kim, B. G., & Lee, S. M. (2007). Removal of heavy metals using waste eggshell. Journal of environmental sciences, 19(12), 1436-1441.

Pedavoah, M. M., Badu, M., Boadi, N. O., & Awudza, J. A. (2018). Green bio-based CaO from guinea fowl eggshells. *Green and Sustainable Chemistry*, *8*(2), 208-219.

Prayitno, B., Musyarofah, M., Tajalla, G. U. N., Nafisah, A. R., Norhidayah, S., & Kartika, S. A. (2025). The effect of calcination temperature and holding time on structural properties of calcia powders derived from eggshell wastE. Indonesian Physical Review, 8(1), 281-299.

Razali, N., Jumadi, N., Jalani, A. Y., Kamarulzaman, N. Z., & Pa'ee, K. F. (2022). Thermal decomposition of calcium carbonate in chicken eggshells: study on temperature and contact time. *The Malaysian Journal of Analytical Sciences*, *26*(2), 347-359.

Rohim, R., Ahmad, R., Ibrahim, N., Hamidin, N., & Abidin, C. A. (2014). Characterization of calcium oxide catalyst from eggshell waste. *Adv Environ Biol*, *8*(22), 35-38.

Selvam, C., Raja, T., Nagappan, B., Upadhye, V. J., Guntaj, J., Devarajan, Y., & Mishra, R. (2025). The role of biodiesel in marine decarbonization: Technological innovations and ocean engineering challenges. *Results in Engineering*, 103974.

Shen, Y., 2017. Rice husk silica derived nanomaterials for sustainable applications. *Renewable and Sustainable Energy Reviews*. **80**: 453-446.

Tsai, W. T., Jiang, T. J., Tang, M. S., Chang, C. H., & Kuo, T. H. (2025). Enhancement of thermochemical properties on rice husk under a wide range of torrefaction conditions. Biomass Conversion and Biorefinery, 15(2), 1825-1834.

Wang, Y., He, T., Liu, K., Wu, J., & Fang, Y. (2012). From biomass to advanced bio-fuel by catalytic pyrolysis/hydroprocessing: Hydrodeoxygenation of bio-oil derived from biomass catalytic pyrolysis. *Bioresource technology*, *108*, 280-284.

Wazir, A. H., Wazir, I. U., & Wazir, A. M. (2024). Preparation and characterization of rice husk based physical activated carbon. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1), 4875-4885.

Witoon, T. (2011). Characterization of calcium oxide derived from waste eggshell and its application as CO2 sorbent. Ceramics International, 37(8), 3291-3298.

Yi, L., Liu, H., Li, M., Man, G., & Yao, H. (2020). Prevention of CaO deactivation using organic calcium precursor during multicyclic catalytic upgrading of bio-oil. Fuel, 271, 117692.

Yi, L., Liu, H., Xiao, K., Wang, G., Zhang, Q., Hu, H., & Yao, H. (2019). In situ upgrading of bio-oil via CaO catalyst derived from organic precursors. Proceedings of the Combustion Institute, 37(3), 3119-3126.

Yi, L., Liu, H., Xiao, K., Wang, G., Zhang, Q., Hu, H., & Yao, H. (2019). In situ upgrading of bio-oil via CaO catalyst derived from organic precursors. Proceedings of the Combustion Institute, 37(3), 3119-3126.

Yusuf, M. (2024). Upgrading of bio-oil model compounds and a sewage sludge oil via hydrodeoxygenation using non-noble transition metal-based catalysts (Doctoral dissertation, University of Birmingham).

Zdravkov, B., Čermák, J., Šefara, M., & Janků, J. (2007). Pore classification in the characterization of porous materials: A perspective. Open Chemistry, 5(2), 385-395.

Zhang, J. X., Guo, Y. T., Zhuang, S. Y., Lou, H. Q., & Li, Y. (2025). The effect of adding rice husk ash (RHA) and calcined shell powder (CSP) on the properties of cement mortar. Case Studies in Construction Materials, 22, e04426.

Zhang, X., Wang, T., Ma, L., Zhang, Q., & Jiang, T. (2013). Hydrotreatment of bio-oil over Ni-based catalyst. *Bioresource technology*, *127*, 306-311.

Zhao, X., Wei, L., Cheng, S., & Julson, J. (2017). Review of heterogeneous catalysts for catalytically upgrading vegetable oils into hydrocarbon biofuels. *Catalysts*, *7*(3), 83.