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Nanocatalyst-driven Sustainable Biodiesel Production from Waste-derived Rubber Seed Oil

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ABSTRACT

The rapid depletion of petroleum reserves and growing environmental concerns have intensified the need for sustainable and renewable energy alternatives. Biodiesel has emerged as a promising substitute for conventional diesel due to its biodegradability and lower environmental impact. In this study, an integrated waste-to-energy approach is explored by utilizing rubber seed oil (RSO), a non-edible and underutilized feedstock, for biodiesel production. A calcium oxide (CaO)-based nanocatalyst derived from prawn shell waste is employed to enhance the sustainability and economic viability of the process. The use of biowaste-derived catalyst not only reduces production cost but also promotes waste valorization. Biodiesel is produced via the transesterification process, and key reaction parameters including catalyst concentration, methanol-to-oil ratio, and reaction time are systematically optimized to maximize yield. The synthesized biodiesel is characterized using Fourier Transform Infrared Spectroscopy (FTIR), along with evaluation of physicochemical properties such as flash point (152ºC), fire point (161ºC), density, and specific gravity. The results demonstrate that the combined use of waste-derived feedstock and catalyst offers a sustainable, cost-effective, and environmentally friendly pathway for biodiesel production.

Keywords: Rubber seed oil; Biodiesel; Extraction; Catalyst.

1. INTRODUCTION

Vegetable oils are gaining attention in the present decade for its renewable nature and seems to be a promising alternative for the diesel fuel (Ramadhas *et al.* 2005). Excellent lubrication, easy storage and free of sulphur, makes vegetable oil suitable for its wide applicability. Feedstock plants used for vegetable oil production act as carbon sinks by absorbing atmospheric CO_2 during photosynthesis, thereby partially offsetting greenhouse gas emissions (Ramadhas *et al.* 2005; Mohd-Setapar *et al.* 2014; Gill *et al.* 2011; Morshed *et al.* 2011; Obunwo *et al.* 2020).

In recent years, systematic efforts have been made by researchers to convert various vegetable oil (palm oil, soya bean oil) to biodiesel (Selaimia *et al.* 2015; Antczak *et al.* 2008; Singh *et al.* 2014; Achten *et al.* 2007; Sayyed *et al.* 2011). The edible oil with lower amount of free fatty acids makes the production of biodiesel economically viable. The higher amount of free fatty acid leads to the formation of soap. Biodiesel produced from edible and non-edible oils are less polluting and are encouraged in developing countries (sayyed *et al.* 2011). The calorific value of biodiesel obtained from vegetable oils are found to be comparable to the commercial diesel. In addition, the substitution of diesel by biodiesel derived from vegetable oil produced in situ in the country generates higher foreign exchange savings including those for major oil exporting countries (Gill *et al.* 2011). This improves the economy and solve the ecological problems of various developing countries. The above stated disadvantages calls for the replacement of fossil fuels for long run. However, viscosity of vegetable oil is comparatively high which makes it unfavourable for its use in direct injection diesel engines due to carbon deposition (Selaimia *et al.* 2015). Fuel impurities can lead to valve clogging, resulting in engine fouling and poor fuel atomization. For the use of biodiesel derived fuel in compression ignition engines, viscosity is reduced by emulsification, pyrolysis, cracking, blending with diesel and transesterification. In the present study, transesterification process is carried out to reduce the viscosity of vegetable oil (Ramadhas *et al.* 2005; Mohd-Setapar *et al.* 2014; Sayyed *et al.* 2011; Ebewele *et al.* 2010).

In the present study, rubber seed oil is used to synthesise biodiesel. Rubber trees are native to south America but are commonly found in southeast Asia (Gill *et al.* 2011; Morshed *et al.* 2011; Zeng *et al.* 2021; Mallika *et al.* 1991). Rubber seed oil (RSO) is obtained from the rubber seeds by extraction. RSO is found to contain palmitic acid (0.2%), stearic acid (8.7%), oleic acid (24.6%), and linoleic (39.6%) acids (Gill *et al.* 2011). In the presence of enzymes, rubber seed is found

to release prussic acid due to the presence of cyanogenic glycosides (Mallika *et al.* 1991; Offurum *et al.* 2017; Kesić *et al.* 2016).

Catalyst prepared from prawn shell waste is used to carry out the reaction. In general, homogeneous or heterogeneous catalysts are employed in the production of bio-diesel. Heterogeneous catalyst like sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium methoxide (CH_3ONa) are widely used. The homogeneous catalyst has several drawbacks due to its complexity in purification step of the produced biodiesel (Thangaraj *et al.* 2019; Okonkwo and Okafor, 2019). Severe problems arise during transesterification caused by large amounts of free fatty acid. Catalytic efficiency is drastically reduced as a smaller amount of catalyst is used for soap formation. Furthermore, large volume of wastewater is generated for removal of residual catalyst during the process of biodiesel purification or washing. Additionally, used catalysts cannot be recovered and backed into the process of biodiesel synthesis (Okonkwo and Okafor, 2016).

In contrast to homogeneous catalysts, removal of heterogeneous catalysts from biodiesel is simple and does not produce wastewater (Okonkwo and Okafor, 2016;). The use of heterogeneous catalysts could enable the design of an efficient, continuous process and improve the economy of biodiesel production. However, the rate of transesterification reaction using heterogeneous catalysts is generally lower than the homogeneous catalysts due to the diffusion of reactants to the active sites of solid catalyst, which is associated with the three-phase system (oil-methanol-solid catalyst). Calcium oxide (heterogeneous catalyst) is favoured as an eco-friendly material that promote longer catalytic activity and requires moderate reaction condition (Thangaraj *et al.* 2019; Okonkwo *et al.* 2016).

Despite extensive research on biodiesel production, several critical challenges remain unresolved, particularly in achieving a cost-effective and sustainable process. Most conventional studies rely on edible oils or refined feedstocks, which raise concerns related to food security and economic feasibility. Although non-edible oils such as rubber seed oil (RSO) have been explored, their utilization remains limited due to issues associated with high free fatty acid content and inefficient conversion processes. In particular, the valorization of biowaste such as prawn shell for the synthesis of calcium oxide-based nanocatalysts has not been extensively investigated in the context of biodiesel production from RSO. Therefore, there exists a significant research gap in integrating waste-derived feedstock and catalyst systems to develop an economically viable, environmentally benign, and efficient biodiesel production process.

2. MATERIALS AND METHODS

2.1 Materials

Rubber seed was collected locally from Kottayam district, Kerala which is known for its rubber cultivation. Prawn shell was collected from local market at Calicut, Kerala. Methanol (≥ 99.9%) and n-hexane (anhydrous, 95%) was purchased from Sigma Aldrich.

2.2 Methods

2.2.1 Extraction of Rubber Seed Oil (RSO)

Rubber seeds collected were dehulled manually to free up kernels from its shell. It was dried in sunlight for about 3-4 days during daylight, powdered by kitchen blender and dried in hot air oven at 60°C for 30 minutes. About 55g of rubber seed powder was taken in extraction thimble, inserted in solvent extraction apparatus and extracted using n-hexane. The soxhlet extraction apparatus was heated to 65°C using heating mantle. The vaporized solvent condensed during the process was filled in the chamber. The process of siphoning occurs when the level of solvent reaches the top and the process is continued for a period of four hours. Oil is recovered from n-hexane by simple distillation. The extraction was also done using water, acetone, ethanol-water and acetone-hexane mixture. The process can be optimized based on yield. RSO was characterized by specific gravity, density, acid value, iodine value and saponification value. Free fatty acid is half the acid value. Lower acid value is preferred for the production of biodiesel, thus, esterification was done to reduce the acid value.

2.2.2 Transesterification Process

Esterification was done by heating 100 ml of RSO at 105°C with constant stirring at 500 rpm. Well mixed methanol and sulphuric acid was added to the oil maintained at 60°C and the reaction was continued for an hour at stirring rate of 600 rpm. Esterified oil was transferred into a separating funnel and allowed to stand for two hours. Pretreated oil was separated from the water formed. Acid value of the esterified oil was observed to determine the feasibility of transesterification reaction.

2.2.3 Preparation of Prawn Shell Catalyst (CaO Based Catalyst)

The catalyst for synthesis of biodiesel was prepared from prawn shell waste. Prawn shell waste was washed thoroughly with hot water to remove unwanted material adhered to its surface and then rinsed twice with distilled water. The washed shells were dried under sunlight for two days, dried in hot air oven at 60°C for 30 minutes. The prawn shell was grounded, crushed and

sieved. 60 g of prawn shell powder was dissolved in 120 ml of 1M HCl. 120 ml of 1M NaOH was added slowly to convert homogeneous calcium chloride solution to sol at ambient temperature and filtered. The filtrate was cleaned with distilled water to remove the impurities in precipitate. The product was dried at 60°C for 24 hours in hot air oven and calcined at different temperatures 500°C, 700°C and 900°C. The catalyst was impregnated by immersing in potassium fluoride solution for an hour. Potassium fluoride (KF) impregnation on CaO nanoparticles was carried out to enhance the basicity and catalytic activity of the catalyst for biodiesel production. KF reacts with CaO to form K_2O/CaO surface species, which increases the number of strong basic sites. These strong basic sites facilitate the deprotonation of methanol, promoting the formation of methoxide ions, which are the active species in the transesterification reaction. This results in higher reaction rate and improved biodiesel yield, especially when converting high free fatty acid oils like rubber seed oil. Additionally, KF impregnation can improve the dispersion of active sites and reduce leaching of the catalyst, contributing to better reusability and stability, which aligns with the sustainability goals of using waste-derived catalysts.

The samples were heated at 373 K for four hours followed by four hours of calcination in muffle furnace at 600°C. Catalyst was characterized by FTIR (Perkin Elmer), SEM (Hitachi SU6600 FE), TGA (Setaram LABSYS EVO) and XRD PANalytical (model X'Pert3 Powder). The particle size of CaO nanoparticles was determined from SEM images using ImageJ software. A total of 100 particles were measured to obtain a representative size distribution, which ranged from 34 nm to 106 nm, with an average particle size of 70 ± 18 nm. CaO nanoparticles were used as a heterogeneous catalyst at varying loadings of 1–5 wt% relative to the oil to optimize biodiesel yield. After each reaction, the CaO catalyst was recovered by filtration, washed with methanol, dried, and reused for up to three cycles with negligible loss in activity

2.2.4 Synthesis of Biodiesel

Synthesis of biodiesel was done by transesterification. A round bottom flask containing mixture of oil, catalyst and methanol was placed inside the oil bath with a condenser connected to it. It was heated to a temperature of 65°C, for alcohol to vaporize. The reaction was performed to obtain the maximum yield and the optimum conditions of biodiesel were determined by varying the process variables; methanol/oil ratio, catalyst concentration and reaction time. After the reaction, the solid catalyst was separated by filtration. The solution was transferred to separation funnel for the layers to separate; top layer holds biodiesel product and glycerol in bottom layer. The amount of biodiesel obtained was quantified by using standard measuring flask. Characterization of biodiesel was done using FTIR, flash point, fire point, specific gravity and density. Excess methanol was recovered by rotary evaporation and reused in subsequent reactions, minimizing solvent consumption

3. RESULTS AND DISCUSSION

3.1 The Effect of Solvent for Oil Extraction

About 27.5 ml of oil was obtained from 55 g of rubber seed powder using n- hexane as solvent. The extracted oil was found to be yellow in colour, clear, transparent and has pleasant odour. n-hexane extract only glyceride compound in rubber seed and tend to exhibit miscibility with RSO. The solvent is found to be non-polar for its C-H bonds and symmetrical structure. Thus, yielding considerable amount of RSO. Water is found to be an ineffective solvent for the extraction process. Using ethanol-water mixture as the solvent, the amount of oil obtained was less (11 ml) compared to that obtained using n-hexane. This might be because in addition to triglycerides, fats and oils contain traces of mono, di and triglyceride, vitamins, albuminous matter and odorous substances. Yield using acetone as solvent was also found to be low due to its dual nature. Acetone exhibits both polar and non-polar nature. This dual nature is due to its ability to make hydrogen bonds with water and presence of methyl groups. Acetone-hexane mixture (40:60) produced higher yield (54.26%) in comparison with other solvents used for extraction. The non-polar nature of both acetone and hexane can be regarded as the reason for higher yield. The yield along with the properties of oil and solvent are shown in table 1. Optimization was done for the acetone-hexane mixture (40:60) at various time intervals. The yield of oil obtained as a function of time for extraction using acetone-hexane mixture (40:60) is shown in Fig. 1. Acetone-hexane mixture (40:60) at six hours was found to be the most suitable solvent for extraction of oil from rubber seed.

When the time was further increased, no increase in yield of oil was observed. Hence the most suitable time for production of oil was found to be 6 hours.

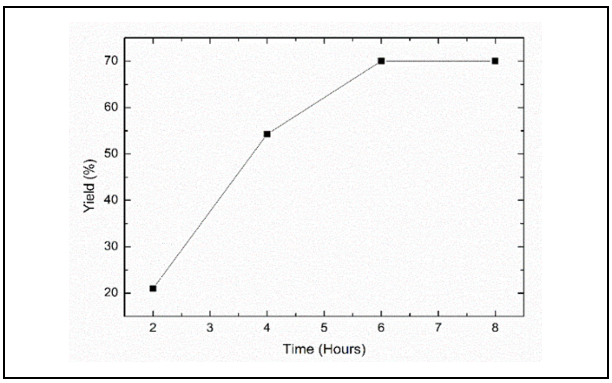


Fig.1: Yield obtained for acetone-hexane mixture (40:60) as a function of time

Table 1. Yield obtained for various solvents along with its properties

Solvent	Yield %	Properties of Oil	Properties of Solvent
Hexane	48.14	Yellow colour, Clear, transparent, pleasant odour	Low polarity, miscible in oil, high solubility, low corrosion, low evaporation loss
Acetone	33.7	Brown colour with pleasant smell	Polar and non-polar solvent
Acetone-hexane mixture (40:60)	54.26	Brown colour	Non-polar
Acetone-hexane mixture (60:40)	38.5	Brown colour	Non-polar
Acetone-hexane mixture (30:70)	43.8	Brown colour	Non-polar
Water	0	Oil could not be extracted	Extraction process is slow
Ethanol-water mixture	17.5	Unpleasant odour, brown in colour	High polarity, immiscible in oil

3.2 Physico-chemical Properties of Rubber Seed Oil

Specific gravity of oil is found to be 0.8859 and density of oil is determined as 0.9628g/cm3. The various parameters determined for RSO along with the values reported in literature for other oil extracts are tabulated in table 2.

Table 2. Comparative study of parameters for various oils

Parameter	Present Study	From Literature (Granados *et al.* 2007; Ramadhas *et al.* 2005)		
		Rubber Seed Oil	Soya Bean Oil	Sunflower Oil
Acid value (mg KOH/gram)	39.27	45	0.1-0.2	0.2-0.5
Free fatty acid (mg KOH/gram)	22.5	22.5	0.05-0.1	0.1-0.25
Saponification value (mg KOH/gram)	193.61	193.61	185-195	187-195
Iodine value (gram iodine/100 gram)	134.51	134.51	124-139	110-144

RSO has high acid value in comparison to soya bean and sunflower oil. Higher the acid value of the oil, higher will be the free fatty acid and it becomes easily exposed to rancidification. RSO can be categorized as semi drying oil with higher iodine value and finds application in the manufacturing of fatty acids, paint, biodiesel and fuel in compression ignition engines. Saponification value of RSO is similar to other typical seed oil such as sunflower oil, soya bean oil and lower than vegetable oils. The value obtained in the present study is in agreement with most of the vegetable oil ranging from 185-253 mg KOH/g. The saponification value of RSO indicates the presence of long chain fatty acids and finds potential application in production of soap and shampoo. In view of high iodine and saponification values of RSO, it is found to be useful in surface coating formulation, soap and biodiesel production.

3.2 Characterization of Catalyst

Catalyst was characterized using FTIR, SEM, XRD and TGA. The FTIR spectra of CaO at different calcination temperatures are shown in Figs. 2-4. The absorption band at 560 cm^{-1} corresponds to Ca-O vibrations, confirming the formation of CaO. A sharp peak observed between 800-900 cm^{-1} at 500°C and 700°C indicates residual $CaCO_3$. This peak disappears at 900°C, suggesting complete decomposition of $CaCO_3$ into catalytically active CaO. The increasing intensity of the 560 cm^{-1} band with temperature indicates enhanced crystallinity, which is favorable for basic site availability.

FTIR confirms the formation of highly basic CaO and successful KF impregnation, both of which are key for promoting catalytic activity in biodiesel synthesis.

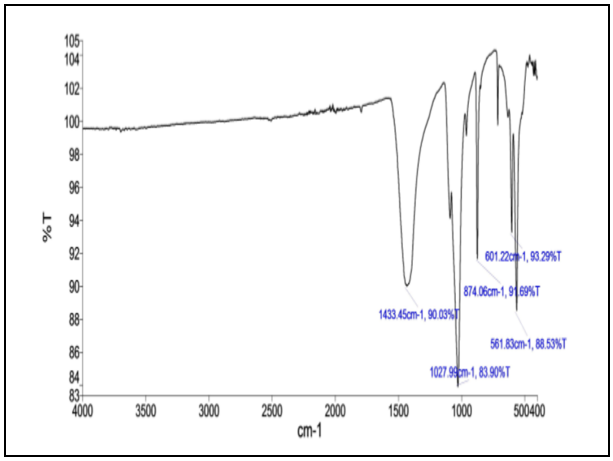


Fig. 2: FTIR spectrum of CaO calcined at 500°C, showing characteristic absorption bands at ~1027 cm^{-1} (O-H stretching due to adsorbed moisture), 1433 cm^{-1} (carbonate stretching), and 874 cm^{-1} (CO_3^{2-} bending), indicating partial surface carbonation of CaO after calcination

The diminished carbonate peak at ~1411 cm^{-1} indicates that most surface carbonates have decomposed at this higher temperature. Peaks at 1030, 874, 601, and

567 cm^{-1} correspond to Ca-O lattice vibrations, confirming the formation of crystalline CaO. A small O-H stretching band suggests minor surface hydroxyl groups remain.

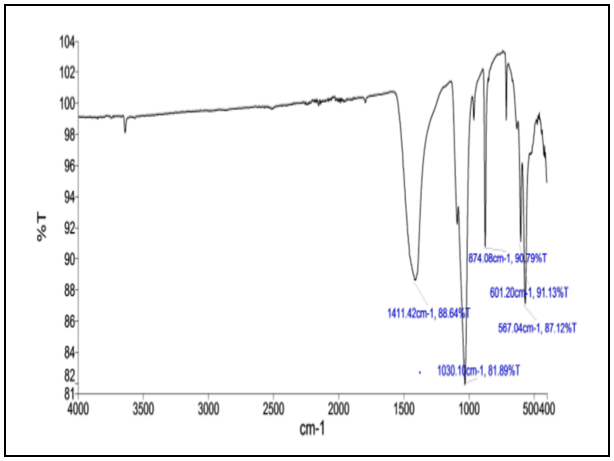


Fig. 3: FTIR spectrum of CaO calcined at 700°C

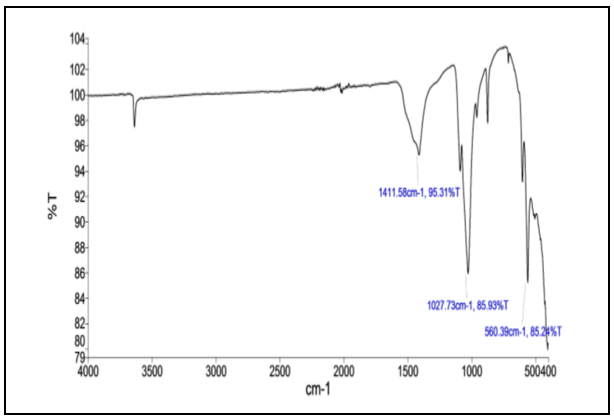


Fig. 4: FTIR spectrum of CaO calcined at 900°C

The very weak carbonate peak at ~1412 cm^{-1} indicates that most surface carbonates have decomposed at this high temperature. The prominent bands at 1028 and 560 cm^{-1} correspond to Ca-O lattice vibrations, confirming the formation of highly crystalline CaO, while the absence of significant O-H stretching suggests nearly complete removal of surface hydroxyl groups.

For the KF-impregnated CaO catalyst, a new band appears at 772 cm^{-1} (Fig. 5), attributed to K-F interactions, confirming successful KF loading. The presence of KF enhances the basicity of the catalyst surface, which is crucial for transesterification reactions. The broader band around 1433 cm^{-1} corresponds to carbonate species (C-O stretching), and its reduced intensity after calcination indicates removal of residual carbonates, increasing the number of active basic sites.

The spectrum shows characteristic absorption bands indicating the presence of key functional groups. The band at ~1415 cm^{-1} corresponds to the asymmetric stretching of CO_3^{2-}, suggesting surface carbonation of CaO. The peak at ~1028 cm^{-1} can be assigned to the stretching of C-O or K-F interactions, indicating incorporation of KF into the CaO matrix. The absorption near 772 cm^{-1} is characteristic of lattice vibrations of CaO, confirming the preservation of the CaO structure after KF modification.

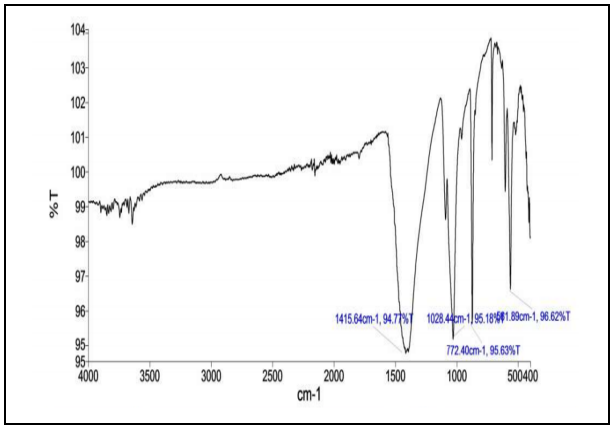


Fig.5: FTIR spectrum of CaO-KF

3.3 Thermogravimetric Analysis

The first weight loss of 0.26 mg found between 50°C to 400°C is due to the removal of $Ca(OH)_2$. A weight loss of 0.39 mg observed at 400°C to 500°C attributes to the decomposition of CaCO3 to CaO along with some loss of inorganic impurities (Singh *et al.* 2014). The TGA data is shown in Fig. 6.

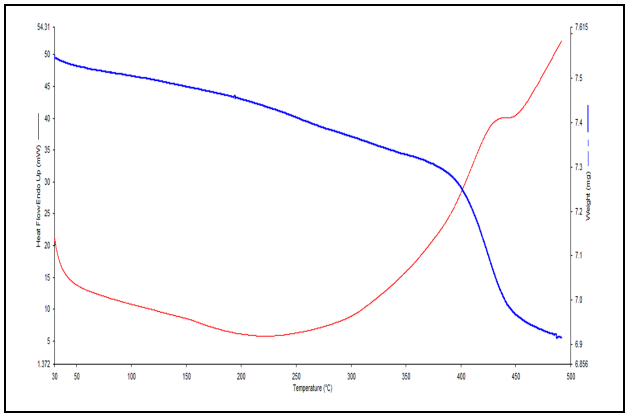


Fig.6: TGA of CaO, showing minor weight loss due to moisture below 150 °C and indicating formation of thermally stable CaO

3.4 XRD Analysis

XRD analysis of CaO nanoparticles was carried out in the 2θ range of 0-90° (Fig. 6). The sharp peaks correspond to the cubic phase of CaO (JCPDS No. 77-2376), confirming the formation of highly crystalline nanoparticles with an average crystallite size of 17.15 nm. The formation of CaO is consistent with the

thermal decomposition of $CaCO_3$, which occurs above ~840°C, releasing CO_2 and leaving CaO. Calcination at 900°C was sufficient to achieve complete decomposition and formation of pure CaO; higher temperatures (e.g., 1100°C) do not significantly alter the crystalline phase but may lead to particle growth. No other characteristic peaks were observed, indicating the absence of residual $CaCO_3$ or impurities.

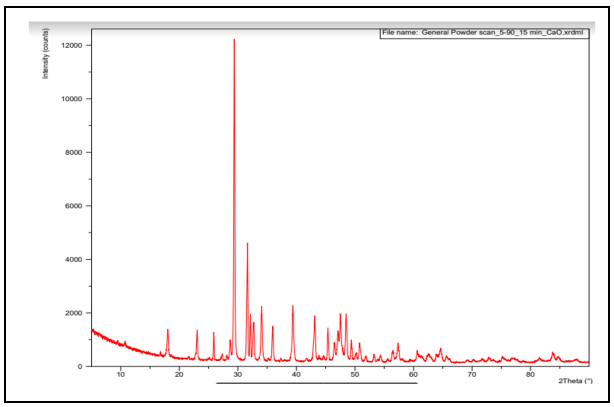


Fig.7: XRD analysis of CaO at 900°C, showing sharp diffraction peaks corresponding to crystalline CaO, indicating complete phase formation and high crystallinity after thermal treatment

3.5 Scanning Electron Microscopy

Fig. 8 shows the SEM image of CaO nanoparticles. The brighter area in the picture reveals the high emission of secondary electrons due to high surface to volume ratio at these areas. Micrograph shows that the synthesized sample have rod like structures. The average grain size of CaO nanoparticles varies from 34 nm to 106 nm. The interaction between nanoparticles with large surface area and high surface energy results in agglomeration. Individual particles seem to be nano-sized plate like crystals and they were partially fused to form hard agglomerates. The presence of pores in the CaO microsphere increases the catalytic activity in biodiesel production by transesterification reaction from oil.

After the acid esterification, the acid value of RSO is found to be 5.61 mg KOH/g and free fatty acid value is calculated as 2.805. The measured FFA value after esterification (2.805 mg KOH/g) remains slightly above the widely accepted threshold (2 mg KOH/g) for efficient transesterification. This implies that although the esterification step reduced the free fatty acid content, it was not sufficiently effective to reduce the FFA value to the optimal level required to prevent soap formation during the subsequent alkaline transesterification stage. The slight increase in the FFA value may lead to reduced biodiesel yield, increased catalyst consumption, and possible emulsification during washing. Further optimization such as tailoring the methanol-to-oil ratio, increasing catalyst, extending reaction time, or additional esterification step might be necessary to achieve a more desirable FFA level and improve overall biodiesel conversion efficiency. The higher value indicates that the amount of free fatty acid has been reduced to significant value after acid esterification.

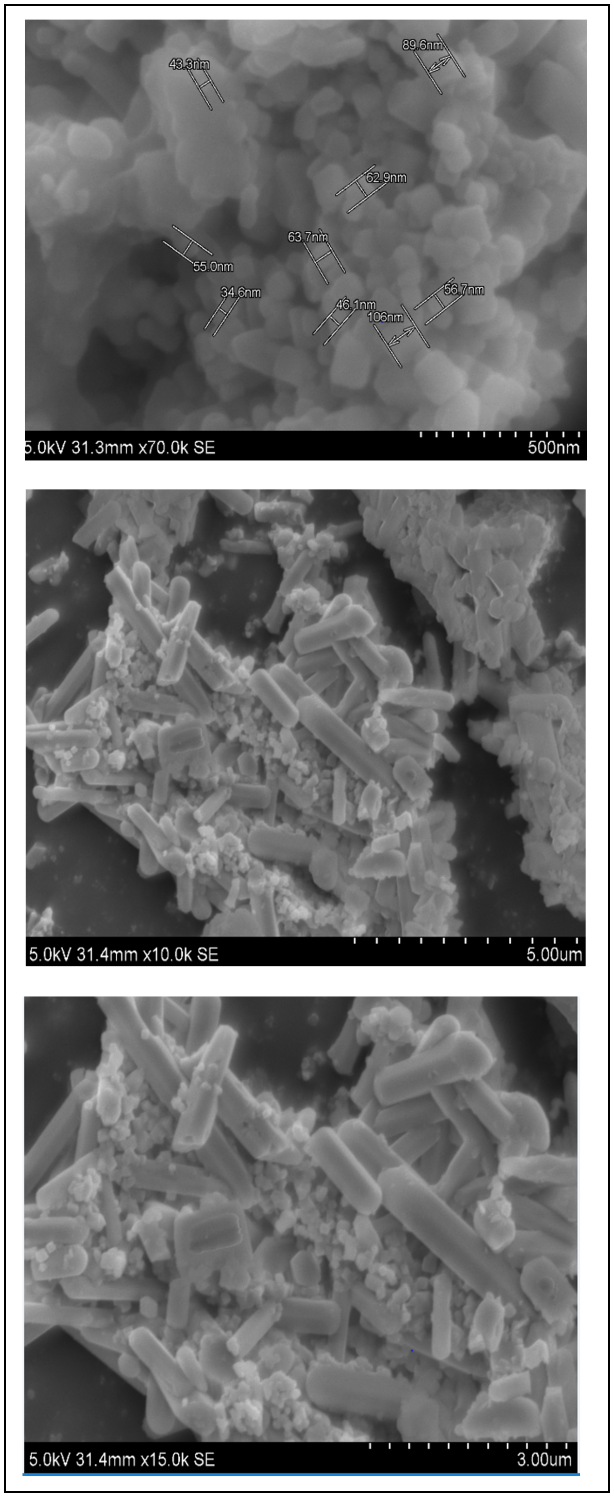


Fig.8: (a), (b) and (c): SEM images of CaO nanoparticles showing irregular and porous morphology with noticeable agglomeration, providing increased surface area that enhances catalytic activity during transesterification

3.6 Characterisation of Bio-diesel

Characterization of biodiesel was done using FTIR and by determining flash point, fire point, specific gravity and density.

FTIR of biodiesel shows a peak at 1589 cm^{-1} representing the stretching of ester group (-C=O). The peak at 1455 cm^{-1} is due to (-C-O) stretching but it has high intensity as the presence of ester group resulted in electronegativity of neighbouring groups. The peak at 2924 cm^{-1} (-C-H- stretching) confirms the formation of biodiesel, indicates symmetric and asymmetric stretching and vibration of methyl group ($-CH_3$) shows characteristic band of fatty acid methyl esters. FTIR of biodiesel is shown in Fig. 9.

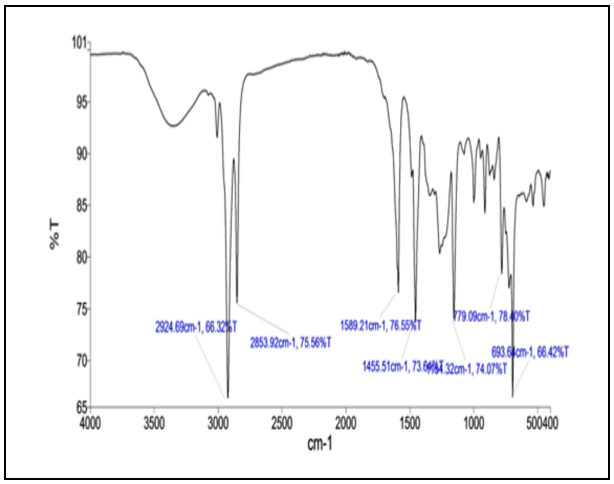


Fig.9: FTIR spectrum of biodiesel showing characteristic peaks corresponding to ester functional groups, including C=O stretching (~1740 cm^{-1}) and C–O stretching (~1170 cm^{-1}), confirming the formation of fatty acid methyl esters (biodiesel)

The flash point of biodiesel from RSO was found to be 152°C, higher than that of high-speed diesel (60-80°C). For non-edible based seed oil, flash point is found to be higher than fossil diesel. Fire point of extracted biodiesel is determined as 161°C. The specific gravity, density and flash point of biodiesel synthesized in present study is compared with the literature and tabulated in Table 3. The synthesized biodiesel was found to have higher flash point than conventional diesel fuel. Density and specific gravity were also found to be slightly higher than conventional fuel. The higher flash point of the biodiesel suggest that the fuel is transportable and is not related to engine performance. The produced biodiesel exhibited a viscosity of ~5 cP, and a calorific value of ~38 MJ/kg, which are comparable to standard biodiesel specifications. These properties indicate good flow behaviour, appropriate fuel density, and sufficient energy content, supporting its suitability as a diesel substitute.

Table 3. Comparative study of properties of biodiesel

Property	Diesel	Biodiesel (Present Study)	Biodiesel (Literature) (Gouveia *et al.* 2017; Sadaf *et al.* 2018; Phankosol *et al.* 2014)
Flash point (° C)	56	152	100-170
Specific gravity	0.85	0.8605	0.86-0.9
Density (g/cm^3)	0.8508	0.8784	0.85-0.9

Optimization of biodiesel properties was done by varying catalyst amount and methanol-oil ratio. The amount of oil obtained as a function of catalyst concentration is shown in Fig. 10 keeping temperature and methanol to oil ratio constant. The optimum catalyst concentration was found to be two grams.

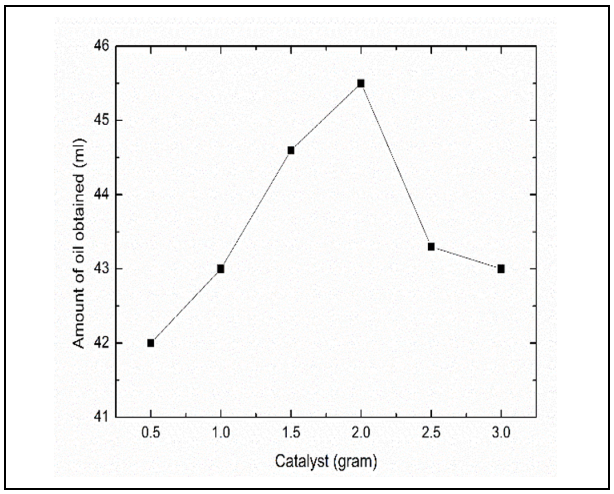


Fig. 10: Amount of oil obtained as a function of catalyst concentration

The optimum value of methanol to oil ratio is tabulated in table 4.

The maximum production of biodiesel was found to be at the methanol-oil ratio of 12:1. The most effective variable affecting the methyl ester production during the transesterification reaction is the molar ratio of alcohol to oil. Since transesterification is an equilibrium reaction, excess alcohol is required for reaction to move forward and avoid the reversible reaction. Four hours was sufficient for maximum biodiesel production. Further increase in time has no significant effect on biodiesel production. From the above experimental results, methanol:oil ratio of 12:1, catalyst concentration of 2 g and four hours reaction time was most suitable for maximum biodiesel production. The maximum yield of 60% was achieved at a 12:1 methanol-to-oil ratio with 4-5 hours reaction time, demonstrating the effectiveness of CaO as a

heterogeneous catalyst for transesterification. The results were reproducible, as confirmed by repeated experiments under identical conditions.

Table 4. Effect of methanol to oil ratio on biodiesel production

Sample	Ratio	Time (Hours)	Product
Sample 1	3:1	3	37 ml biodiesel, 30 ml glycerol
Sample 2	3:1	4	40.5 ml biodiesel, 26 ml glycerol
Sample 3	6:1	3	42 ml biodiesel, 22 ml glycerol
Sample 4	6:1	4	45.5 ml biodiesel, 15 ml glycerol
Sample 5	9:1	3	52.6 ml biodiesel, 11 ml glycerol
Sample 6	9:1	4	54 ml biodiesel, 9 ml glycerol
Sample 7	12:1	3	57 ml biodiesel, 4 ml glycerol
Sample 8	12:1	4	60 ml biodiesel, 2 ml glycerol
Sample 9	12:1	5	60 ml biodiesel, 2 ml glycerol

4. CONCLUSIONS

Rubber seed oil (RSO), owing to its high iodine and saponification values, demonstrates significant potential as a non-edible and sustainable feedstock for biodiesel production. The use of an acetone–hexane (40:60) solvent system was found to be most effective for oil extraction, attributed to its optimized polarity for enhanced oil recovery. Furthermore, the valorization of prawn shell waste for the synthesis of a calcium oxide (CaO)-based nanocatalyst provides a cost-effective and environmentally sustainable approach, while SEM analysis confirms the formation of nanoscale catalytic structures that enhance reaction efficiency.

Biodiesel produced via transesterification of RSO was successfully characterized using FTIR, confirming the presence of key functional groups associated with fatty acid methyl esters. The fuel properties, including flash point, were found to be superior to conventional diesel, indicating improved safety in handling and storage. Under optimized conditions of methanol-to-oil ratio of 12:1, catalyst concentration of 2 g, and reaction time of 4 hours, a maximum biodiesel yield of 60% was achieved. Further increase in catalyst concentration resulted in only marginal improvement in yield, indicating an optimal threshold for catalyst utilization.

Although the reaction time was observed to have limited influence beyond the optimal duration, this behaviour may be attributed to the attainment of equilibrium conditions, beyond which no significant conversion enhancement occurs. However, further kinetic studies are required to substantiate this observation. Overall, the integration of waste-derived feedstock and catalyst presents a sustainable and economically viable pathway for biodiesel production. Future work should focus on engine performance evaluation, emission analysis, and the application of nano-additives to further enhance combustion efficiency and reduce emissions, thereby advancing the practical applicability of this biodiesel in the transportation sector

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Achten, W. M. J., Mathijs, E., Verchot, L., Singh, V. P., Aerts, R. and Muys, B., Jatropha biodiesel fueling sustainability? Biofuels, *Bioprod. Biorefin*., 1(4), 283-291(2007). https://doi.org/10.1002/bbb.39

Antczak, M. S., Aneta, K., Tadeusz, A. and Stanisław, B., Enzymatic biodiesel synthesis–key factors affecting efficiency of the process, *Renew. Energy*, 34(5), 1185-1194(2009). https://doi.org/10.1016/j.renene.2008.11.013

Ebewele, R. O., Iyayi, A. F. and Hymore, F. K., Deacidification of high acidic rubber seed oil by reesterification with glycerol, *Int. J. Phy. Sci*., 5(6), 841-846(2010). http://www.academicjournals.org/IJPS

Gill, P., Soni, S. K., Kundu, K. and Srivastava, S., Effect of blends of rubber seed oil on engine performance and emissions, *Fuel,* 88, 738-743(2011).

Gouveia, L., Oliveira, A. C., Congestri, R., Bruno, L., Soares, A. T., Menezes, R. S., Filho, N. R. A. and Tzovenis, I., Biodiesel from microalgae, In Microalgae-based biofuels and bioproducts, Woodhead Publishing, *Elsevier,* 235-258(2017). https://doi.org/10.1016/B978-0-08-101023-5.00010-8

Granados, M. L., Poves, M. D. Z., Alonso, D. M., Mariscal, R., Cabello, G. F., Tost, M. R., Santamaria, J. and Fierro, J. L. G., Biodiesel from sunflower oil by using activated calcium oxide, *Appl. Catal. B: Environ.,* 73(3-4), 317-326(2007). https://doi.org/10.1016/j.apcatb.2006.12.017

Kesić, Ž., Lukić, I., Zdujić, M., Mojović, L. and Skala, D., Calcium oxide based catalysts for biodiesel production: a review, *Chem. Indus. Chem. Eng. Quarterly*, 22(4), 391-408(2016). https://doi.org/10.2298/CICEQ160203010K

Mallika, G. V., Jansz, E. R., Nirmala, P. M. and Abeysekara, A. M., Cyanogenic Glucosides and Glucosidases of Rubber Seed Kernel, *J. Natn. Sci. Coun. Sri Lanka,* 19(2), 99(1991). https://doi.org/10.4038/JNSFSR.V19I2.8157

Mohd-Setapar, S. H., Nian-Yian, L. and Mohd-Sharif, N. S., Extraction of rubber (Hevea brasiliensis) seed oil using soxhlet method, *Malaysian J. Fundament. Appl. Sci*., 10(1), (2014). https://doi.org/10.11113/mjfas.v10n1.61

Morshed, M., Ferdous, K., Khan, M. R., Mazumder, M. S. I., Islam, M. A. and Uddin, M. T., Rubber seed oil as a potential source for biodiesel production in Bangladesh, *Fuel*, 90(10), 2981-2986(2011). https://doi.org/10.1016/j.fuel.2011.05.020

Obunwo, C., Osagie, O. F. and Jack, A. D., Evaluation of Bioplastics Production Potentials of Rubber Seed Oil and Cocoyam Starch, *Chem. Res. J.,*5(2), 108-114(2020).

Offurum, J. C., Dike, M. C., Akuchie, C. J., Nwaneri, T. U. and Mbadike, C. A., Effects of process parameters on mildsteel corrosion inhibition by ethyl ester of rubber seed oil, *J. Sci. Multidis. Res*., 9(2), (2017).

Okonkwo, S. I. and Okafor, E. C., Determination of the proximate composition, physicochemical analysis and characterization of fatty acid on the seed and oil of Gossypium hirsutum, *Int. J. Chem*., 8(3), 57-61(2016). https://doi.org/10.5539/ijc.v8n3p57

Phankosol, S., Kaokanya, S,, Supathra, L., Kornkanok, A. and Kanit, K., Estimation of density of biodiesel, *Energy Fuels,* 28(7), 4633-4641(2014). https://doi.org/10.1021/ef501031zRamadhas, A. S., Jayaraj, S. and Muraleedharan, C., Biodiesel production from high FFA rubber seed oil, *Fuel*, 84(4), 335-340(2005). https://doi.org/10.1016/j.fuel.2004.09.016

Ramadhas, A. S., Jayaraj, S. and Muraleedharan, C., Biodiesel production from high FFA rubber seed oil, *Fuel*, 84(4), 335-340(2005). https://doi.org/10.1016/j.fuel.2004.09.016

Sadaf, S., Sahar, Javed, I., Inam, U., Haq, B. N., Shazia, N., Rehman, H. U., Jan, N. and Munawar, I., Biodiesel production from waste cooking oil: an efficient technique to convert waste into biodiesel, *Sustain. Cities Soc*., 41, 220-226(2018). https://doi.org/10.1016/j.scs.2018.05.037

Sayyed, S. R., Gitte, B. M., Joshi, S. D. and Dharmadhikari, H. M., Characterization of biodiesel: a review, *Int. J. Eng. Res. Technol*., 2(10), (2011). https://doi.org/10.17577/IJERTV2IS100795

Selaimia, R., Abdelsalem, B. and Rabah, O., The synthesis of biodiesel from vegetable oil, *Procedia Soc. Behav. Sci.,* 195, 1633-1638(2015). https://doi.org/10.1016/j.sbspro.2015.06.221

Singh, D., Rohidas, B., Anuradda, G. and Sanjay, M., Synthesis of biodiesel from vegetable oil using supported metal oxide catalysts, *Energy fuels*, 28(4), 2743-2753(2014). https://doi.org/10.1021/ef500045x

Thangaraj, B., Solomon, P. R., Muniyandi, B., Ranganathan, S. and Lin, L., Catalysis in biodiesel production—a review, *Clean Energy*, 3(1), 2-23(2019). https://doi.org/10.1093/ce/zky020

Zeng, H., Wu, J., Zhu, X., Singh, A. K., Chen, C. and Liu, W., Jungle rubber facilitates the restoration of degraded soil of an existing rubber plantation, *J. Environ. Manage.*, 281, 111959(2021). https://doi.org/10.1016/j.jenvman.2021.111959