Eco-Friendly Nano Catalyst Preparation for Biodiesel Production from Melia azedarach Seeds: A Step Toward Climate Mitigation

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Biodiesel is a renewable and sustainable alternative to fossil fuels, offering a cleaner source of energy with significantly reduced greenhouse gas emissions. This study explores the production of biodiesel from non-edible Melia azedarach seed oil using green synthesis through TiO_2 nanocatalysts. Oil was extracted using n-hexane, and transesterification was performed under different conditions of the molar ratio of oil-to-methanol (1:3, 1:6, 1:9, 1:12, and 1:15), temperatures (70, 80, 90, 120, and 140 °C), concentration of TiO_2 catalyst (0.3, 0.5, 0.7, 0.9, and 1 g), and reaction times (1, 2, 3, 4, and 5 hours). Maximum biodiesel yield (93%) was achieved when the molar ratio was 1:12, the temperature was 80 °C, the weight of the TiO_2 catalyst was 0.7 g, and the reaction time was 3 hours. Fourier Transform Infrared Spectroscopy, X-ray Diffraction (XRD), and Scanning Electron Microscopy (SEM) were used to characterize the TiO_2 nanocatalyst and verified its catalytic activity and structure. The FTIR characterization of the produced biodiesel verified the presence of methyl esters. The use of non-edible feedstock like Melia azedarach is eco-friendly since it is not in food-vs-fuel competition and can be grown on marginal lands. Secondly, the method combats global climate change by minimizing the use of fossil fuels and carbon emissions. Through this research, it is proven that biodiesel synthesis using non-edible feedstock (Melia azedarach seed oil) is a sustainable method of climate-resilient large-scale biodiesel production in accordance with renewable energy and climate resilience criteria.

Keywords: Biodiesel, Melia Azedarach, Climate Change, Transesterification.

Introduction:

An increased human population and industrialization have enhanced the use of fossil fuels, creating climate change and shifting weather patterns [1]. Biodiesel, a bio-based, renewable, and nontoxic alternative fuel, is being researched as a long-term solution. Bioenergy already accounts for half of the world's renewable energy sources, and it has the potential to address global energy and climate change challenges [2]. Biodiesel is derived from plant-based waste oils that are affordable, easily accessible, and renewable [3]. Biodiesel is less harmful than regular diesel and degrades faster, reducing environmental impact [4]. There are several well-known technologies such as transesterification, direct use and blending, micro-emulsions and pyrolysis for producing biodiesel fuels. To improve the volatility and lower the viscosity of motor fuel, lipids (vegetable oils or animal fats) are trans esterified. Transesterification is one of the most widely used methods of producing biodiesel. Because of its simplicity, it is one of the most widely used methods of producing biodiesel. It involves a reversible reaction between lipids (triglycerides) and short-chain alcohols (such as methanol, ethanol, or propanol) in the presence of an appropriate catalyst, resulting in the formation of fatty acid alkyl esters (biodiesel) and glycerol [5]. Optimization of the transesterification process is crucial for efficient biodiesel production [6]. Micro emulsion is a physical method for using vegetable oil in diesel engines without chemical treatment. It creates a transparent and stable oil-surfactant dispersion, due to their higher alcohol content, methanol and vegetable oil microemulsions have a lower calorific value than diesel, but they perform nearly as well in terms of engine operation [7]. Blending is another method, which reduces viscosity, acid composition, and lubricating oil thickening [8]. Pyrolysis is becoming increasingly important in the energy market due to its high-value products. Researchers have focused on optimizing pyrolysis settings for high-quality biofuel generation [9]. The production of biodiesel involves four types of catalysts: homogeneous, heterogeneous, enzymatic, and Nano catalyst [10]. Homogeneous catalysis is the most common, as it is simple and takes less time to complete the reaction [11]. Acids like sulfonic and sulfuric acids and hydrochloric acids catalyze the esterification process, providing high yields of alkyl esters. However, these catalysts are sensitive to FFAs and water, making them expensive [12].

The heterogeneous acid catalysts, i.e., zeolites and acid-functionalized mixed metal oxides, can catalyze both the esterification and transesterification reactions at the same time [13]. Enzymatic biodiesel production is very eco-friendly, and lipases are the most widely used enzymes [14]. The two significant challenges in employing lipases as catalysts for the transesterification reactions of the biodiesel process are that their activity is significantly lower compared to chemical catalysts and that they are deactivated by lower alcohols [15]. Nanocatalysts are nanomaterials whose particle sizes vary between 1 and 100 nm and are particularly valuable in heterogeneously catalyzed biodiesel production because they are selective, energy efficient, and catalytically active [16]. They are useful as they are recyclable, generate minimal waste, and can easily be purified. Two different nanocatalysts with 20 nm and 50 nm particle sizes were prepared for biodiesel production by a wet impregnation method [17]. Some other effective solid catalysts are Li2CO3 [18], Li2TiO3 [19], Li-modified rice husk ash [20], LiAlO2 [21], CaO/CuFe2O4 (Seffati et al., 2019), and AC/CuFe2O4@CaO [22][23].

Akhtar et al., 2023 used non-edible seed oil from *Descurainia sophia* to synthesize Cerium oxide nanocatalyst for sustainable biodiesel production. Analytical techniques showed the nanocatalyst's three-fold reusability and its dependability and effectiveness in transesterification reactions. Baskar et al., 2022 synthesized a mechanism using a zinc-doped iron nanocatalyst and tetrabutylammonium iodide as a co-catalyst for producing biodiesel from used cooking oil. Optimizing transesterification parameters, they achieved a 90% biodiesel conversion at 55°C and 50 minutes, with the biodiesel primarily composed of methyl esters.

Global dependence on fossil fuels continues to contribute significantly to greenhouse gas emissions and climate change. While biodiesel offers a cleaner alternative, many current production methods rely on edible feedstocks, exacerbating food security concerns. There is a pressing need to identify non-edible, sustainable biodiesel sources and develop efficient synthesis methods. This study addresses the challenge by exploring the use of Melia azedarach oil, a non-edible, marginal land-friendly feedstock processed via green TiO_2 nanocatalyst-assisted transesterification, to optimize biodiesel yield and contribute to environmentally friendly energy solutions.

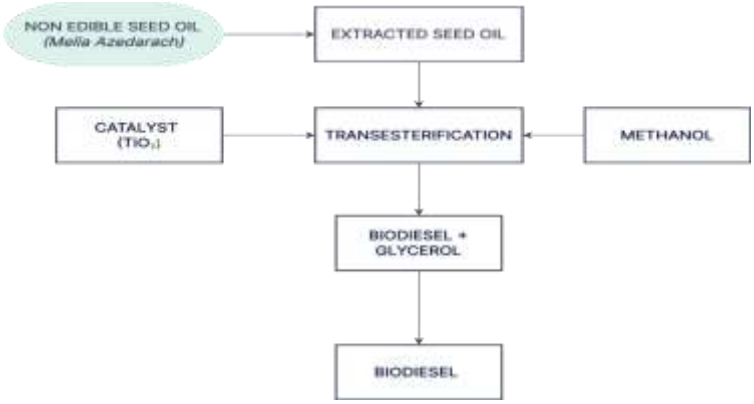

Figure 1. Flowchart of biodiesel production through nanocatalyst of TiO_2

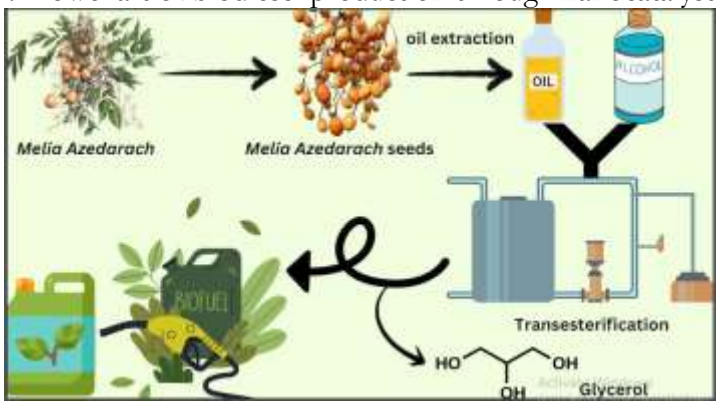

Figure 2. Production of biodiesel from Melia azedarach seeds

The present work reports the production of fatty acid methyl esters (biodiesel) from Melia azedarach seed oil via optimized green TiO_2 nanocatalyst based transesterification with methanol. The leaf extract of the locally accessible plant *Melia azedarach* contains phytochemicals and reducing agents that act as stabilizing and reducing agents. As such, it offers a scalable alternative to physical or chemical methods for green nanoparticle synthesis. The novelty of this research lies in the synthesis of a green nanocatalyst using Melia azedarach leaf extract supported on TiO_2. Catalyst synthesis with this combination and its application in biodiesel synthesis is relatively unexplored in the literature. Furthermore, advanced analytical techniques were employed to examine the synthesized green TiO_2 nanocatalyst and biodiesel.

Materials and Methodology:

Equipment and Chemicals:

Digital Weighing Balance (GF-3000), Conical Flasks, Beakers (100 and 500 ml), Filter Paper (Wattman 42), Aluminum Foil, Pipette, Iron Stand, Electric Oil Expeller (KEK P0015, 10127 Germany), Burette, Soxhlet Assembly (Behr Labor – Technik), Magnetic Stirrers, Dropper, Drying Oven (DHG-9053A), Calcination Furnace (Neycraft), Distilled Water, Ethanol, Titanium Oxide, Phenolphthalein, Potassium Hydroxide (KOH), and Isopropanol. All the analytical grade reagents were bought from Merck (Germany), Scharlau (Spain), and

Sigma Aldrich (USA).

Seed Collection:

Melia azedarach seeds were collected from the International Islamic University, Islamabad. The seeds were initially dried in the sun and oven-dried at 60 °C for 24 hours to remove off the moisture and powdered finely in a grinder to ascertain the seed oil content.

Oil Content Determination:

The soxhlet method was employed to determine the oil content (Figure 3). For condensation, 300 mL of n-hexane was poured in to round bottom flasks and coupled to a continuous water supply. The flask was kept under constant heat to reflux at a pre-set temperature (60 °C). The solvent kept evaporating from the thimble to the condenser after boiling, and vapors became caught in the thimble. The extract was filtered through thimble pores of filter paper, and then into the bottom flask through the siphon tube. It took approximately 5-6 hours to accomplish this process. The solvent that was used was recovered with the aid of a rotary evaporator to purify the oil, and the resultant product was oven dried and weighed to estimate the oil content. The experiment was performed thrice, and the resulting oil was stored in a safe container for further research [24].

Mechanical Extraction:

Mechanical extraction is also one of the oldest methods of oil extraction. Seeds are put between barriers where available space for the seed is restricted by compressing in most cases, causing oil to be pressed out of the seeds. Mechanical pressing is the most popular method of oil extraction and employs a motorized screw press or hydraulic press. Although efficient, mechanical pressing has a tendency to yield relatively small quantities of oil.

Oil Filtration:

The oil is then passed through a series of filters to remove any remaining solid particles, such as seed particles or other debris. In this process, slowly pour the oil into the filter funnel, allowing it to pass through the filter paper. Gravity or mild pressure can be used to facilitate the flow. The filter paper acts as a barrier, trapping impurities, solid particles, and other contaminants present in the oil while allowing the filtered oil to pass through.

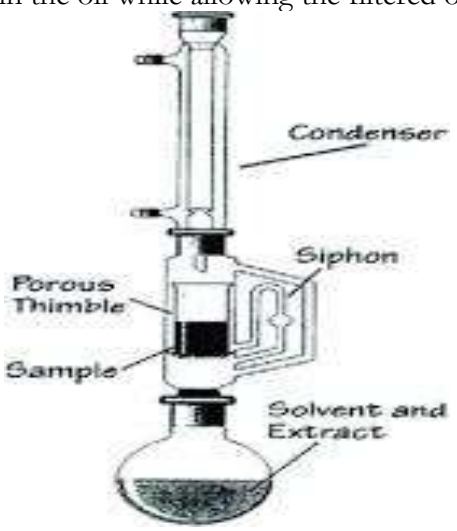

Figure 3. Soxhlet apparatus for the oil extraction process [25].

Determining The Free Fatty Acids Content:

Two types of titration methods were used to measure the free fatty acid (FFA)content of Melia azedarach's seed oil i.e. Blank titration and sample titration.

Blank Titration:

For the blank titration, a conical flask containing 10 mL of isopropanol and three drops of phenolphthalein indicator was titrated with 0.025 M KOH solution until a persistent pink color appeared, at which point the volume was recorded.

Sample Titration:

For the sample titration, 1 mL of *Melia azedarach* seed oil was combined with 9 mL of isopropanol, followed by the addition of 2–3 drops of phenolphthalein indicator. This mixture was then titrated with a KOH solution until a persistent pink color appeared, indicating the endpoint.

Leaf Extract Preparation:

Titanium-based green NPs were produced from Melia azedarach's leaf extract using the biological approach. Melia azedarach's leaves were taken from the International Islamic University Islamabad. To eliminate dust, the leaves were rinsed with distilled water and dried for 20 minutes. Small chunks of dried leaves were cut. Place 20 g of chopped leaves in a beaker with 500 mL of distilled water and heat on a hot plate at 70 °C until half the water had evaporated. The dilute liquid was filtered using Whatman's filter No. 1 after it had cooled to room temperature.

Tio_2 Nanocatalyst Synthesis:

To make the Titanium nanocatalyst, a 0.5 M solution of TiO_2 was solution was made by dissolving 18.76 g of Titanium (IV) oxide in distilled water and stirring at 600 rpm for 1 hour. A dilute solution of the green leaf extract was added to the Titanium oxide solution and heated continuously until the solution color changed to a white-yellowish semi-liquid, indicating the formation of titanium oxide NPs. The semi-liquid was allowed the semi-liquid to settle for 24 hours. The uppermost layer of water was removed, and the concentrated solution was put into the Petri plates (Figure 4) in the bottom layer. For drying, keep the Petri plates in the oven at 60 °C until thoroughly desiccated.

Figure 4. Synthesized nanocatalyst from TiO_2

Characterization Of Nanocatalyst:

X-Ray Diffraction (XRD):

The synthesized nanocatalyst was characterized using X-ray diffraction (XRD) with a Bruker D8 Advance instrument to confirm crystallite formation. The crystallite size was calculated using the Debye–Scherrer equation. XRD patterns were recorded over a 2θ range of 10° to 80°.

Scanning Electron Microscopy (SEM):

Morphological analysis was performed using scanning electron microscopy (SEM) with a JEOL JSM-5910 model. SEM images were captured at an accelerating voltage of 5 kV using a field emission electron microscope (Akhtar et al., 2023). This analysis provided qualitative insights into the structural features of the catalyst and its support, revealing changes that occurred during calcination and pretreatment.

Fourier Transform Infrared (FTIR) Analysis:

Fourier-transform infrared (FT-IR) spectroscopy was employed to detect and analyze the organic functional groups and inorganic ions present in *Melia azedarach* biodiesel. The analysis was carried out using a BRUKER TENSOR 27 spectrometer over a spectral range of 3,500 to 400 cm^{-1}, with a resolution of 1 cm^{-1} and 15 scans per sample. FT-IR spectra were obtained for the seed oil, the resulting biodiesel, and the catalysts, following the approach outlined by [26].

Biodiesel Synthesis:

Biodiesel was produced from seed oil using the reflux transesterification method. The materials involved in the process included a nanocatalyst, seed oil, a hot plate, a magnetic stirrer, a thermometer, and a reflux condenser. The reaction was conducted in a 250 mL round-bottom flask equipped with a thermometer, magnetic stirrer, and reflux setup. Initially, 0.1 g of nanocatalyst was refluxed with methanol and oil at a molar ratio of 1:3 for 1 hour at 70 °C. After the system cooled slightly, preheated seed oil was added, and the mixture was refluxed again at the same temperature for an additional 2 hours. Once the reaction was complete, the mixture was allowed to cool and then transferred to a separating funnel. The resulting two-phase mixture separated into an upper layer of crude biodiesel (fatty acid methyl ester) and a lower layer of glycerol.

Characterization of Biodiesel:

FTIR:

Fourier-Transform Infrared (FT-IR) spectroscopy was conducted using a PerkinElmer Spectrum 65 instrument (Waltham, MA, USA) to analyze the functional groups based on vibrational motions of atoms and molecules present in the oil and biodiesel samples. The spectral data were collected within the range of 4000 to 500 cm^{-1}, using a resolution of 1 cm^{-1} and a scanning rate of 15 scans, following the procedure described by [27].

Biodiesel optimization:

The biodiesel optimization process was performed in the following ways,

Oil Methanol Ratio:

One of the important parameters influencing the chemical and technical aspects of biodiesel production is the molar ratio of oil to methanol. Based on stoichiometric calculations, 3 moles of methanol are required for each mole of oil to produce 3 moles of methyl esters (biodiesel) and 1 mole of glycerol. However, due to the reversible nature of the transesterification reaction, this ratio is typically insufficient to drive the reaction to completion. Therefore, an excess of methanol is commonly used to shift the equilibrium toward biodiesel formation. When using a heterogeneous catalyst, an even higher methanol-to-oil molar ratio is often necessary to achieve optimal conversion.

Catalyst Concentration:

Green TiO_2 nanocatalyst possesses typical catalytic surface sites**, ** which render it extremely effective for the catalytic reaction. The catalyst concentration needs to be controlled to regulate the rate of the transesterification reaction. The catalyst has to be optimized so that the yield of biodiesel is maximized. A variable level of the catalyst concentration was used between 0.3 – 1 g% (wt. of catalyst) and its influence on Melia azedarach seed oil transesterification was analyzed. The reaction was carried out at 80 °C with 2 hours of reaction time and a 1:12 oil-to-methanol ratio.

Reaction Temperature:

The transesterification of MASO was carried out at various temperatures ranging from 70 °C to 140 °C with a constant reaction time (2 hours), a concentration of catalyst (0.7 g)**,** and an oil-to-methanol ratio (1:12).

Reaction Time:

Reaction time is also an important parameter to be considered in determining the cost of production of biodiesel. The influence of reaction time on Melia azedarach seed oil biodiesel (MASOB) was studied by varying the reaction time from 1 to 5 hours with other parameters kept constant (a 1:12 molar ratio between oil and alcohol, 0.7 g concentration of nanocatalyst, and **a** temperature of 80 °C).

Results and Discussion:

Oil Content and Free Fatty Acid (FFA) Composition:

The extracted oil yield from Melia azedarach seeds reached 36 wt%, which significantly

exceeds the sustainability benchmark of 20–25% for biodiesel feedstocks. This highlights Melia azedarach as a compelling non-edible candidate for commercial-scale biodiesel production. [28] similarly emphasized the potential of oil-abundant seeds such as Jatropha curcas and Terminalia catappa, both of which surpass the 30% oil content mark, making them ideal due to their negligible impact on food security and high oil recovery efficiency.

The measured FFA content was 1.204 mg KOH/g, which is well within the acceptable range for a single-step, base-catalyzed transesterification process. Oils with FFA levels exceeding 3% typically require acid-catalyzed pretreatment to avoid soap formation. [29] highlighted that low FFA values below 2% not only improve catalyst stability but also enhance biodiesel yield, particularly in systems employing heterogeneous catalysts.

Characterization of Tio_2 green nanocatalyst:

X-ray Diffraction (XRD):

X-ray diffraction analysis is the most widely used method for characterization of nanocatalysts. The XRD spectra of the synthesized TiO_2 nanocatalyst revealed sharp diffraction peaks appearing at 2θ = 27.60°, 29.57°, 36.22°, and 54.46° as shown in (Figure **5**) and can be indexed to (100), (101), (200), and (111) lattice planes of a cube. The average crystallite size corresponding to the prominent (100) peak was calculated using the Debye–Scherrer equation.

$$D = K\lambda / \beta \, Cos\theta \qquad (1)$$

In this equation, D represents the crystallite size in nanometers, λ is the wavelength of the Cu-Kα X-ray radiation, K denotes the shape factor, β is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg angle. The calculated average crystallite size was 5.5 nm, indicating the material's nanoscale dimensions and high degree of crystallinity. Moreover, the diffraction peaks observed at 27.60°, 36.22°, and 54.46° support the rutile structure of the material. The broad diffraction peaks characterize the very limited region of crystallite, and the size of the XRD sample's points indicates that the targeted nanoparticles remained crystalline [22]. According to [30], TiO_2 nanoparticles in the 5–10 nm range exhibit superior surface activity and facilitate efficient transesterification. Crystallite sizes below 6 nm have been associated with a 20–25% improvement in biodiesel conversion compared to larger particles.

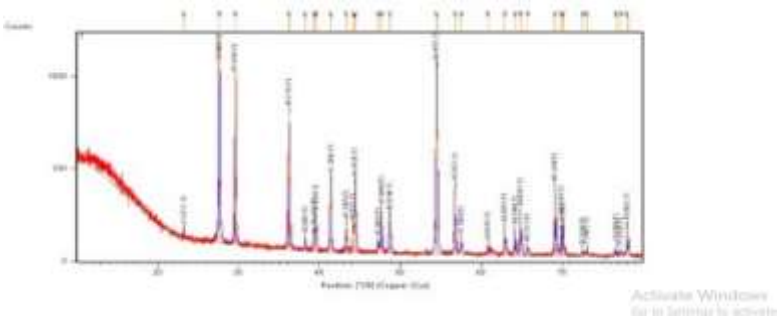

Figure 5. X-ray diffraction analysis of TiO_2

Scanning Electron Microscopy (Sem):

Scanning Electron Microscopy (SEM) was used in the study to visualize the external morphology, size and form of titanium oxide nanoparticles that were made with Melia azedarach leaf extract. The nanoparticles were mostly spherical and had an average size of 50-80 nm (Figure.6). The accurate assessment of nanoparticle size was made possible by the strong differentiation between individual particles in high resolution SEM images. SEM imaging showed a tetragonal morphology with uniformly distributed TiO_2 nanoparticles synthesized via green methods. This structure enhances interaction between the catalyst and oil molecules. [31] reported similar morphologies in TiO_2 nanoparticles derived from neem and moringa extracts, attributing increased reactivity to the presence of bioactive compounds

in the green synthesis route.

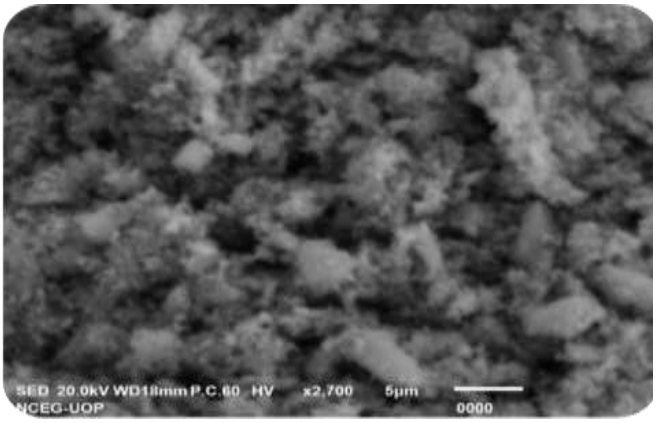

Figure 6. SEM analysis of titanium oxide (TiO_2)

FTIR Spectroscopy:

Fourier Transform Infrared (FTIR) is a spectroscopy method that can be used to identify organic, polymeric and inorganic materials. In other words, FTIR identifies variations in the total composition of compounds through the determination of changes in the functional groups in biomolecules. FTIR provides detailed information about the composition and molecular structure of a sample by absorption of infrared radiation at different wavelengths. The FTIR spectrum is plotted with absorption intensity on the y-axis and wavenumber on the x-axis showing the identification of various functional groups present in the sample.

The presence of the metal oxide stretching vibrations of titanium oxide in the prepared nanocatalyst is reflected by the strong absorption band between 3453.22 $cm^{-1,}$ and 95.85 cm^{-1} (Figure 7). The O-H bond bending and stretching mode is reflected by the weaker absorption peak at 1425.86 cm^{-1} and 78.57 cm^{-1}. Due to the numerous phytochemicals that exist in the leaf extract, the 875.11cm^{-1} and 81.67cm^{-1} peak is assigned to the stretching vibration of the aromatic compounds C≡C.

The broad extended band at 497.45 cm^{-1} and 15.20 cm^{-1} is a bending vibration mode of a hydroxyl group, marking the adsorption of an adsorbed water molecule over the surface of the nanocatalyst.

Water adsorption by the nanocatalyst certifies that the fabricated nanocomposite possesses an extremely large surface area. FT-IR data, therefore, validate XRD data and certify the fabrication of an extremely pure TiO_2 nanocatalyst.

The FTIR spectra confirmed the presence of characteristic metal-oxygen (Ti–O) bonds and surface hydroxyl groups. These functional groups validate the formation of TiO_2 nanoparticles and suggest enhanced methanol adsorption capacity, which can accelerate the transesterification process [32]. Additionally, bio-organic compounds introduced through green synthesis may contribute to improved surface reactivity and long-term catalyst stability.

Optimization of Biodiesel Yield:

A series of experiments were conducted by considering four main variables i.e nanocatalyst concentration, oil to methanol ratio, reaction temperature and reaction time to determine the suitable conditions for maximum biodiesel yield.

Nanocatalyst Concentration:

An important parameter in biodiesel yield is catalyst concentration. The reaction was performed at 80 °C with a reaction time of 2 hours while using a 1:12 oil: methanol ratio. The results indicated that biodiesel yield increased significantly (Figure.8) when there was an increase in the catalyst concentration from 0.5 – 0.7g. A biodiesel yield of 87 wt% was attained at an optimum catalyst concentration of 0.7g. However, biodiesel yield was reduced when the catalyst concentration exceeded 0.9% to 1%. Varying TiO_2 catalyst concentrations revealed

that 0.7 g was optimal, producing an 87% biodiesel yield. Higher concentrations negatively impacted yield, likely due to increased viscosity and reduced mass transfer efficiency. According to [9], high catalyst concentration causes the soap formation because of emulsification. Similar findings by [33] indicate that excessive catalyst loading can lead to particle agglomeration, hindering reaction kinetics and decreasing biodiesel yield.

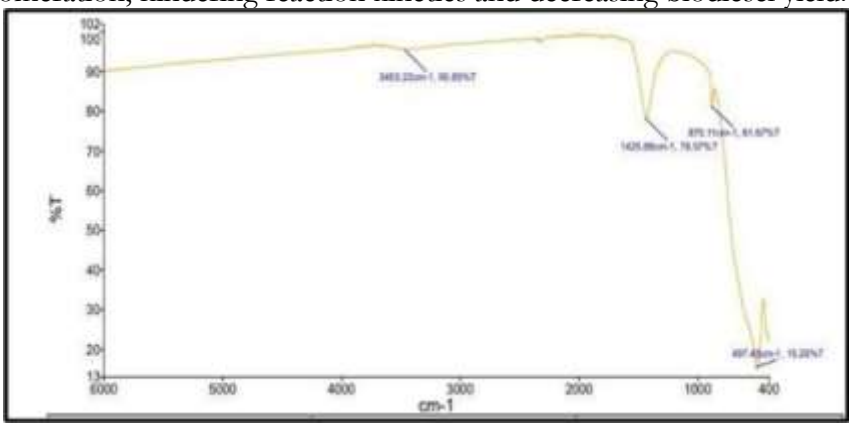

Figure 7. FTIR analysis of TiO_2

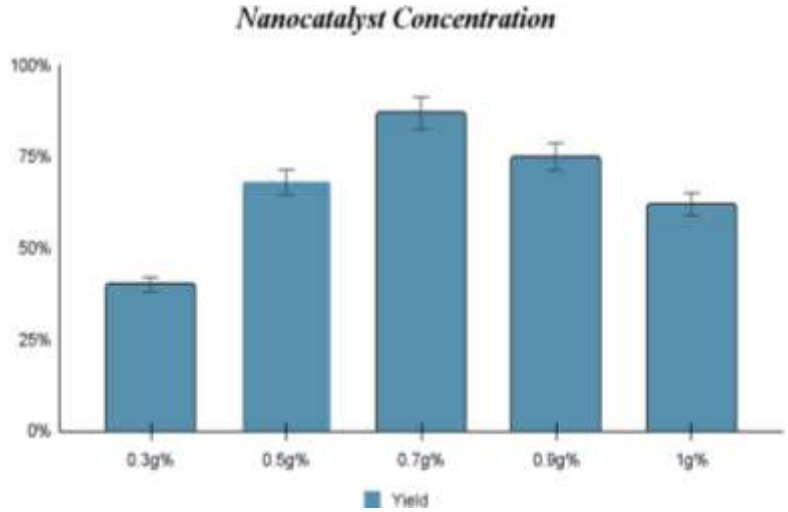

Figure 8. Effect of catalyst concentration on Biodiesel Yield

Oil to Methanol Ratio:

The molar ratio of oil to methanol had a substantial influence on biodiesel yield. In this study, we employed different oil to methanol ratios i.e., 1:3, 1:6, 1:9, 1:12, 1:15. The results clearly revealed (Figure 9) that the maximum biodiesel yield of 90 wt% was achieved at a 1:12 oil to methanol ratio. According to the literature, the transesterification reaction is reversible in nature and the stoichiometric requirement is 3:1. The yield of biodiesel was found to be increased with an increasing oil to methanol ratio but after 1:12 the decline in biodiesel yield was observed. These results are in agreement with the literature and suggest that the optimum oil to methanol ratio is between 1:9 to 1:12 [34]. The decline in biodiesel yield is due to the use of excess methanol which complicates downstream separation and decreases overall yield due to phase imbalance.

Reaction Temperature:

Reaction temperature is also a deciding factor in biodiesel yield. It has been noted that increasing the temperature speeds up the reaction process and boosts product yield; this could be because rising temperatures decrease oil viscosity, facilitating oil-alcohol mixing and enhancing the separation of glycerol from biodiesel. In this study (Figure 10), different reaction temperatures were used i.e., 70 °C, 80 °C, 90 °C, 120 °C, 140 °C were used to determine the

ideal temperature for maximum biodiesel yield. The highest biodiesel yield (93 wt%) was attained at 80 °C which the increase in temperature resulted in a decline in biodiesel yield. As shown in the figure after increasing the reaction temperature to 120°C, the production of biodiesel drops to 72 % and at a temperature of 140°C, the production of biodiesel drops to 40%. This decline at high temperatures is due to high miscibility that results in the reduction of phase separation as well as biodiesel yield. [35] similarly found that high temperatures could destabilize the catalyst surface, negatively affecting biodiesel quality.

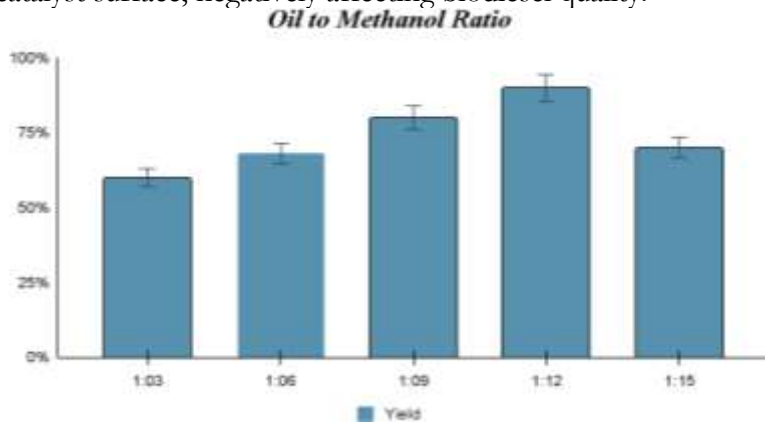

Figure 9. Effect of Oil to Methanol Ratio on Biodiesel Yield

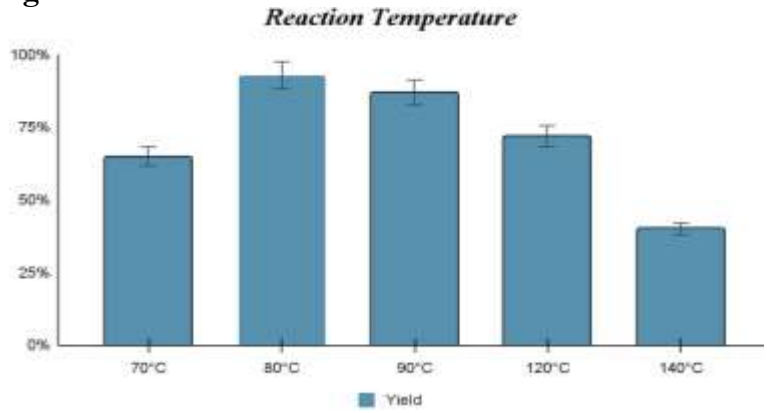

Figure 10. Effect of Reaction Temperature on Biodiesel Yield

Reaction Time:

The effect of reaction time on biodiesel yield was analyzed by using transesterification reaction over a period of 1 to 5 hours by keeping all other parameters constant. The biodiesel yield at different reaction times is shown in (Figure 11). It was observed that biodiesel yield significantly increased from 1 hour to 3 hours after which a decline was observed. This decline is due to the prolonged reaction which introduced processing and potential product degradation (enhanced hydrolysis of ester). These observations align with [36], who caution that excessive reaction times may lead to lower energy efficiency and decreased biodiesel yield.

Biodiesel Characterization (FTIR):

FT-IR analysis is utilized to detect numerous functional groups in biodiesel samples using the mid-infrared region. A wide range of peaks were observed between wavelengths 1500 cm^{-1} to 500 cm^{-1} representing ester formation. Figure 12 depicts the FTIR spectrum of *Melia azedarach's* biodiesel. Several stretching vibrations in the spectrum show the creation of different functional groups in the biodiesel sample (Dawood et al., 2021). Peaks observed at 3325.94 cm^{-1}, 2944.56 cm^{-1} and 2832.86 cm^{-1} represent O-H stretching of carboxylic acid. However, the distinctive band appeared at 1449.05 cm^{-1} are for ester stretch, corresponding to methyl ester group. Peaks appeared at 1113.63 cm^{-1} and 1021.14 cm^{-1} are typical for C-O stretch of the methoxy carbonyl group of biodiesel. The sharp peak at 609.67 cm^{-1} is typical

for -CH_3 (Alkyl) bending [37]. FTIR analysis confirmed the presence of characteristic functional groups associated with biodiesel. Similar bands were observed in previously reported work further validate the structural integrity of the synthesized product [10].

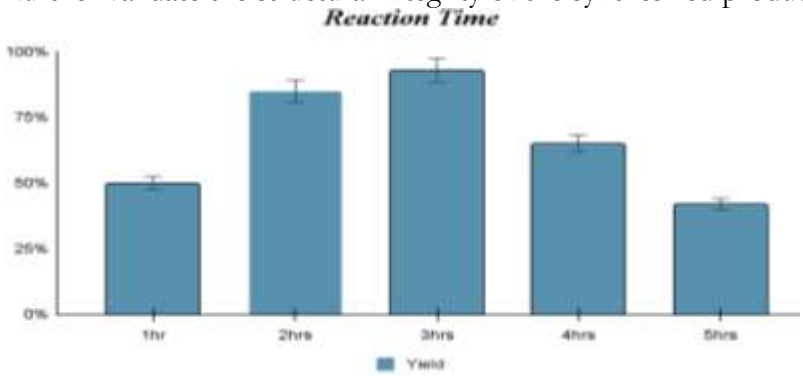

Figure 11. Effect of reaction time on the biodiesel yield.

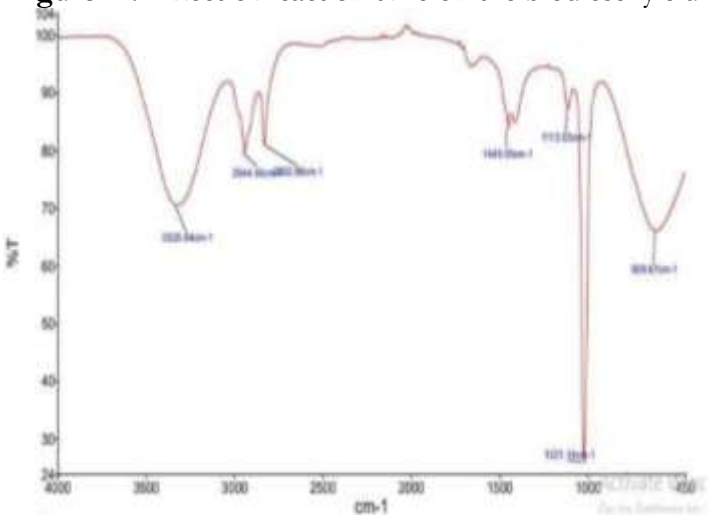

Figure 12. FTIR of Melia azedarach's Biodiesel

Conclusion:

The comprehensive evaluation of *Melia azedarach* seed oil as a biodiesel feedstock affirms its suitability for sustainable fuel production. With an impressive oil yield of 36 wt% and an FFA content of 1.204 mg KOH/g, the seed oil supports a streamlined, single-step transesterification process. Coupled with the high catalytic efficiency of green-synthesized TiO_2 nanoparticles—confirmed through XRD, SEM, and FTIR analyses, the study achieves an optimized biodiesel yield of up to 93% under favorable conditions.

From a climate perspective, these results carry significant implications. Biodiesel derived from non-edible feedstocks such as Melia azedarach offers a renewable, low-emission alternative to fossil fuels. Unlike petroleum-based diesel, biodiesel combustion results in substantially reduced greenhouse gas emissions, particularly carbon dioxide and particulate matter. Additionally, the use of plant-based and waste-derived catalysts aligns with circular economy principles and reduces reliance on energy-intensive synthetic methods.

As global temperatures rise and fossil fuel reserves dwindle, transitioning to sustainable biofuels is no longer optional it's imperative. Research like this underscores the importance of developing low-cost, non-food biodiesel sources that minimize environmental impact, strengthen energy resilience, and contribute meaningfully to climate mitigation strategies.

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