Waste to Wheels: Bio-Diesel Synthesis from used Cooking Oil

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Abstract—
With the world's growing energy demand and increasing environmental concerns, adopting sustainable and eco-friendly energy sources has become a pressing necessity. This project explores an innovative solution that tackles two major problems simultaneously waste management and clean energy production. India produces about 3 million metric tons of used cooking oil (UCO) annually, with 60% reused in food, risking health issues like heart disease and cancer. Much of the rest discarded or underused for biodiesel. Repeated frying raises free fatty acid levels, increasing health risks. This project converts UCO into renewable, biodegradable biodiesel, providing a cleaner diesel alternative while reducing environmental and health hazards.
Biodiesel synthesized from used cooking oil via transesterification using methanol and NaOH. The final product met ASTM D6751 standards, with a viscosity of 4.56 mm^2/s, density of 925 kg/m^3, flash point of 182 °C, and calorific value of 39,216 kJ/kg slightly lower than diesel but with improved combustion stability. Engine tests was conducted on diesel, B20, and B20 blends enhanced with ZnO nanoparticles synthesized from cow dung (B20-25 NP and B20-50 NP). The B20-50 NP blend showed the best performance, achieving a brake thermal efficiency of 35.55% and the lowest specific fuel consumption (0.26 kg/kWh). Emissions of HC (3ppm), CO (0.02%), and NO_x (602 ppm) significantly reduced, with a slight increase in CO_2 indicating more complete combustion. The results highlight the potential of nanoparticle-enhanced biodiesel as a cleaner and more efficient alternative fuel.
Our findings reveal that the biodiesel derived from waste cooking oil meets quality benchmarks such as less emission compared to normal diesel, also offers a cost- effective and environmentally responsible alternative to non-renewable fuel. This project opens an opportunity to supports circular economy by converting waste into a valuable product. It serves as a small but meaningful step toward a cleaner, more sustainable future.
Keywords – Used Cooking Oil, Biodiesel, nanoparticles, circular economy.

I. INTRODUCTION

With the global population expanding rapidly and economies continuing to grow, the demand for fossil fuels has surged dramatically. Yet, these energy sources are finite and being consumed at an unsustainable rate. As supplies dwindle, fuel prices climb, putting increasing financial pressure on individuals, industries, and governments. On top of the economic impact, the widespread use of fossil fuels is a leading contributor to greenhouse gas emissions, which play a major role in driving air pollution, global warming, and climate change [6].

The environmental consequences of this ongoing fossil fuel dependency are just as concerning as the economic ones. Extracting and burning these fuels only worsens environmental degradation, making it clear that there is an urgent need to transition to cleaner, more sustainable energy solutions. Today, the world finds itself at a critical crossroads, facing both an energy crisis and environmental decline. In response, renewable energy sources such as wind, solar, and especially biofuels are gaining momentum. Among these, biodiesel stands out for its sustainable origins, ability to work with existing diesel engines, and its comparatively low environmental impact [1].

As this dual crisis intensifies, the search for energy alternatives that align with environmental and economic goals has become more urgent than ever. Biofuels like biodiesel have emerged as practical and promising options. In recent years, biodiesel has attracted increasing interest for its cleaner combustion, energy efficiency, and environmentally friendly profile, offering a sustainable alternative to fossil-based diesel and contributing to a more secure and greener energy future [2].

a) Challenges and Opportunities in Managing UCO

As consumption of food rises and the food service industry continues to expand especially in densely populated countries like India the amount of Used Cooking Oil (UCO) generated is becoming a growing concern. The Food Safety and Standards Authority of India (FSSAI) reports that India produces nearly 3 million metric tons of UCO every year. What is troubling is around 60% of this oil finds its way back into the food chain after it has reused multiple times, particularly by street vendors and small eateries. Repeated use of cooking oil increases the levels of Free Fatty Acids (FFAs), which has linked to serious health problems like heart disease and even cancer [3].

Beyond the health risks, the way UCO is often disposed of poured down drains or dumped in landfills poses a major threat to the environment. These careless practices contaminate water sources, degrade soil quality, and strain urban waste management systems.

This situation highlights the urgent need to raise awareness among the public and food businesses about the dangers of mismanaging UCO. One of the most effective and sustainable solutions lies in converting UCO into biodiesel. Instead of becoming waste, used oil is repurposed as a clean, renewable fuel helping to build a circular economy where waste is turned into a valuable resource [9].

Producing biodiesel from UCO not only reduces our dependence on imported fossil fuels but also boosts national energy security and supports climate goals by cutting down on harmful vehicle emissions. In short, repurposing UCO for biodiesel tackles multiple challenges at once protecting public health, improving environmental quality, and promoting sustainable energy use [5].

b) Objectives of the Work

To develop a sustainable, environmentally friendly fuel alternative by converting used cooking oil into bio-diesel.

SPECIFIC OBJECTIVES

1. To synthesis bio-diesel from spent cooking oil at lab scale.
2. To investigate the quality of Bio-diesel produced from Used Cooking Oil.
3. To Evaluate the Performance of Bio-diesel produced from Used Cooking Oil in Engine Applications using Green synthesized Catalyst.
4. Utilization of Byproducts Obtained from the Biodiesel Production.

II. LITERATURE REVIEW

The literature paints a comprehensive picture of biodiesel from Used Cooking Oil not just as a technically sound solution, but also as a pathway toward environmental sustainability and economic resilience. It is a compelling example of how something as ordinary as used cooking oil can become a powerful tool in our transition to cleaner, more responsible energy systems.

The researcher conducted research on "Determination of Free Fatty Acid in Frying Oils of Various Foodstuffs" [4], focusing on how repeated frying affects the free fatty acid (FFA) levels in cooking oils used for different food items like chicken, catfish, and flour-based foods using an acid-base titration method. The researchers concluded that excessive reuse of cooking oil leads to a substantial rise in FFA content, posing both health and environmental risks and highlighting the importance of pre-treatment when using such oils for biodiesel production.

Author carried out a study titled "Investigation of Biodiesel Production by Altering Free Fatty Acid Content in Vegetable Oils" [8], where they analysed how varying FFA levels in different vegetable oil blends affect biodiesel yield. The findings underscore the importance of selecting appropriate pretreatment methods based on FFA content for efficient biodiesel conversion.

Scholar presented a comprehensive review titled "Biodiesel Production Through Chemical and Biochemical Transesterification: Trends, Technicalities, and Future Perspectives" [7]. This work outlined and compared traditional chemical methods (alkali and acid catalysis) with enzymatic (biocatalytic) transesterification techniques. The authors noted that chemical methods can achieve biodiesel yields exceeding 90% under optimal conditions, typically with a methanol-to-oil molar ratio of 6:1 and reaction temperatures between 50°C and 65°C. The authors emphasized the need for sustainable practices, recommending low-cost, waste-derived feedstock's and reusable heterogeneous catalysts to reduce production costs and improve environmental outcomes.

III. METHODOLOGY

This section describes the materials used and the experimental procedures adopted for the synthesis and characterization of biodiesel derived from waste cooking oil. The methodology was designed to convert used cooking oil into biodiesel through a transesterification process and to evaluate its fuel properties, engine performance, and emission characteristics.

a) Materials

UCO: Used cooking Oil was collected from a variety of places around the city, including popular street-side Gobi stalls, the Government hostel mess, and catering services at local marriage functions. It is identified as the main feedstock for biodiesel production because it is readily available, low-cost and its reuse helps prevent environmental pollution and health impacts.

Methanol: Methanol is commonly selected for making biodiesel because it is affordable and highly reactive. In the transesterification process, it plays a key role by reacting easily with vegetable oils or animal fats.

Sodium hydroxide (NaOH): It is used as a homogeneous catalyst in the transesterification process. Being a strong base, it speeds up the reaction between Used Cooking Oil and methanol to produce biodiesel.

Green-synthesized ZnO nanoparticles: These are selected for their environmentally friendly and sustainable production method, offering a cleaner alternative to conventional chemical or physical synthesis techniques. These nanoparticles act as nano-additives and are blended with the prepared biodiesel to enhance engine performance and reduce exhaust emissions.

b) Method

This section explains the step-by-step process followed to produce and analyze biodiesel from Used Cooking Oil. It began with pre-treating the oil and measuring its free fatty acid (FFA) content, followed by the transesterification reaction to produce biodiesel. Zinc oxide (ZnO) nanoparticles were also prepared using an eco-friendly, green synthesis method. After production, the biodiesel tested for its fuel properties, engine and emission performance were evaluated. Additionally, the glycerol byproduct generated during the process was put to good use by converting it into soap, reducing overall waste.

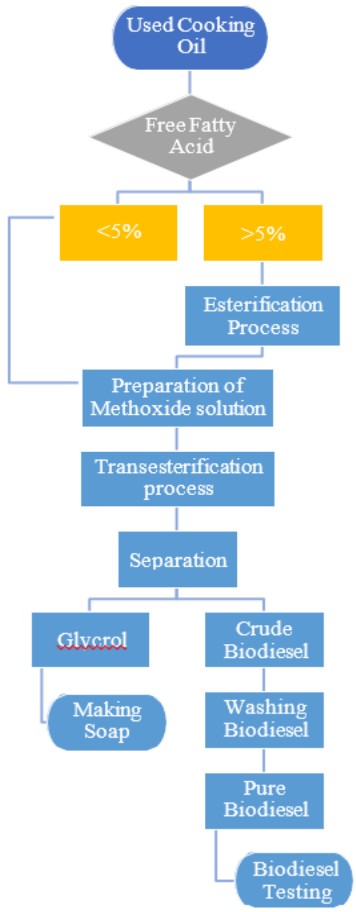

Figure 1: PFD of synthesizing bio-diesel

The collected UCO was gently heated on a hot plate to about 60°C to 70°C for 10 minutes. This step helped remove moisture and made the oil less thick, allowing heavier particles to settle faster. After heating, the oil was filtered to get rid of any solid impurities. This heating and filtering routine was repeated three times to ensure the oil was clean and ready for the transesterification process, improving the overall biodiesel production.

Free fatty acid was determined titration method and the values were calculated using the below equation.

$$\text{FFA (\%)} = \frac{V \times N \times 28.2}{W} \qquad (1)$$

The filtered oil is heated to around 60°C on a hot plate. A standard oil-to-methanol ratio of 1:6 is used, and sodium hydroxide (NaOH) is added as a catalyst based on 1% of the oil's FFA content. The methanol and NaOH were mixed well to create a methoxide solution, which is then poured into the preheated oil. This mixture is stirred continuously and kept between 60°C and 70°C for about 1.5 to 2 hours to complete the reaction.

After the reaction, the mixture is left to settle in a separating funnel for up to 8 hours or overnight. This separates the mixture into two layers: the top layer is the biodiesel (methyl ester), and the bottom layer is glycerol, which can sometimes become partly solid. The biodiesel is washed with hot water, using an equal amount of water and biodiesel heated to between 40°C and 60°C. This step removes soap, glycerol, leftover methanol, and other impurities. Next, the cleaned biodiesel is heated again at 100°C to 110°C for about 10 minutes to get rid of any remaining moisture and volatile substances like alcohol. Finally, the purified biodiesel is stored in an airtight container. The quality of the biodiesel produced is checked according to the ASTM standards.

$$\text{BD yield} = \frac{Weight\ of\ BD\ produced}{Weight\ of\ oil\ used} \times 100 \qquad (2)$$

IV. RESULTS AND DISCUSSION

This chapter shares the results of the biodiesel made from used cooking oil. The biodiesel was tested for important fuel properties and compared against ASTM standards as well as regular diesel. The byproduct glycerol from the transesterification process was used to prepare soap, and results are discussed. Key findings include fuel property analysis, catalyst characterization, engine performance, and dry washing of biodiesel using fine soil. Data is presented through figures, tables, and graphs, and compared with standard values.

a) Free fatty acid in UCO

The free fatty acid (FFA) content in the used cooking oil was measured by titrating the oil with a standard sodium hydroxide (NaOH) solution, using phenolphthalein as an indicator. The values are shown in Table 1.

Table 1. FFA % of UCO

Sample Type	Kitchen Oil	Hostel Mess Oil	Catering Oil
FFA (%)	3.84	2.4	1.5

b) Biodiesel yield from UCO

Biodiesel was successfully synthesized from UCO collected from various. A total of 6 liters of UCO was collected and used for the experiment. Table 2 presents experimental conditions for biodiesel synthesis.

Table 2. Experimental conditions for BD production

Parameter	**Value**
UCO	1 liter per batch
Methanol	210 mL (approx. 21% v/v of oil)
NaOH Catalyst	6.5 grams per liter of oil (based on FFA content)
Reaction Time	1.5 hours
Reaction Temperature	Maintained between 60°C and 70°C

Figure 2. Visual workflow of Biodiesel production using UCO

c) Comparison of biodiesel with standards

All the physical property tests were performed following ASTM standards in the laboratory the University. Table 3 shows a comparison of these properties between commercial diesel and biodiesel (the prepared biodiesel).

Table 3. Comparison of Physical Properties – Diesel vs. BD vs ASTM/EN Standards

Sl. No.	**Property**	**Diesel**	**BD**	**ASTM Limits (B6–B20)**
1	Calorific Value (kJ/kg)	42,000	39,216	39,000–42,000*
2	Flash Point [°C]	52–96	182	93
3	Fire Point [°C]	62–106	134	---
4	Density at 15 °C [Kg/m^3]	824	925	860-900 (EN Std)
5	Viscosity [mm^2/s]	1.2–2	4.56	1.9–4.1
6	Cetane Number	48	55	Min. 40

d) Engine performance results

Brake Thermal Efficiency (BTHE) measures how well an engine converts the energy in fuel into useful mechanical power by comparing the engine's brake power output to the fuel's energy input.

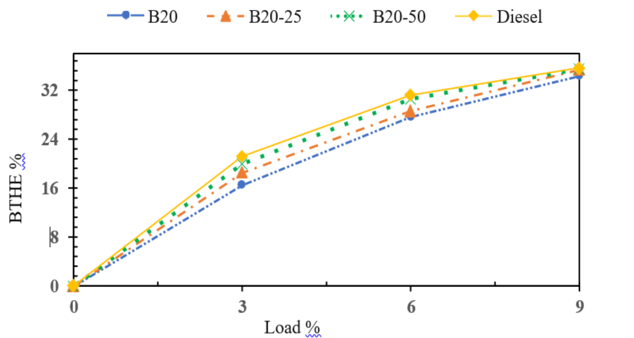

Figure 3. BTHE level across diesel and BD blended with Zno nanoparticles.

Specific Fuel Consumption (SFC) measures an engine's fuel efficiency by showing how much fuel is used to produce a unit of brake power (kg/kWh). It reflects how well the engine converts fuel into power.

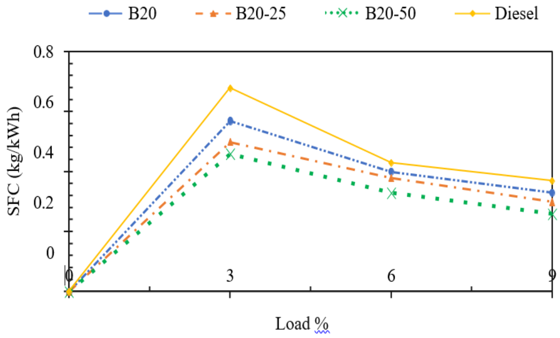

Figure 4. SFC level Across Diesel and Biodiesel Blends with ZnO Nanoparticles.

The engine's emissions were measured using an exhaust gas analyzer under different load conditions. The analysis focused on key pollutants like hydrocarbons (HC), nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). Tests were carried out for diesel, B20 biodiesel, and B20 blends with green-synthesized ZnO nanoparticles to see how adding nanoparticles affected emissions.

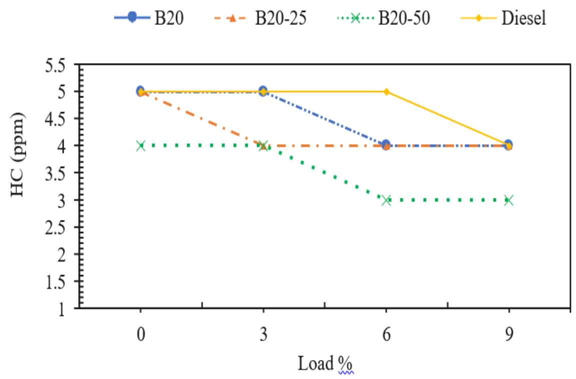

Figure 5. HC Emission Levels Across Diesel and Biodiesel Blends with ZnO Nanoparticles.

Hydrocarbon (HC) emissions indicate the presence of unburnt fuel, reflecting incomplete combustion. Figure 5 illustrates how HC emissions vary for diesel, B20 biodiesel, and ZnO-blended B20 fuels across different engine loads.

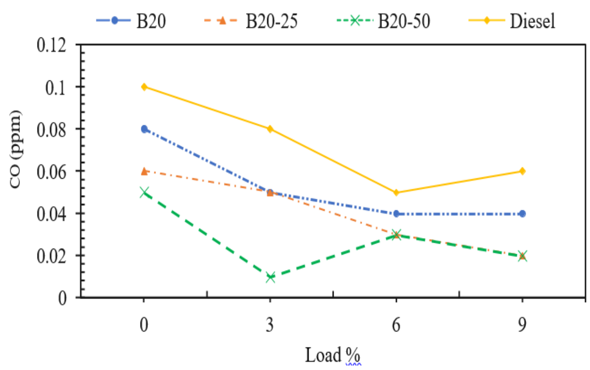

Figure 6. CO Emission Levels Across Diesel and Biodiesel Blends with ZnO Nanoparticles.

Carbon monoxide (CO) is produced when combustion is incomplete, making it a harmful pollutant. Figure 6 shows how CO emissions change for diesel, B20 biodiesel, and ZnO-blended B20 fuels under different engine loads.

For all fuels, CO emissions decreased as the engine load increased, indicating better combustion efficiency at higher loads. Among the fuels tested, the B20 blend with 50 mg of ZnO nanoparticles (B20-50) had the lowest CO emissions across all load levels, followed by B20-25, plain B20, and diesel. For example, at a 9 kg load, CO emissions were 0.06% for diesel, 0.04% for B20, and just 0.02% for both B20-25 and B20-50 respectively.

V. CONCLUSION

The work explored how effectively biodiesel can produced from Used Cooking Oil and how well it performs in engine applications.

A total of 4 liters of biodiesel successfully synthesized from 6 liters of Used Cooking Oil (UCO), yielding an average conversion efficiency of 70%. Compared to diesel, BD has a slightly lower calorific value of 39,216 kJ/kg compared to 42,000 kJ/kg for diesel. BTHE increased with engine load for all fuels, with diesel reaching 35.61%, while B20-25 and B20-50 achieved 35.4% and 35.55%, respectively, due to improved combustion from ZnO nanoparticles. ZnO-blended B20 fuels show improved emission performance. At full load, HC emissions dropped to 3 ppm (from 4 ppm in diesel), and CO emissions reduced to 0.02% (from 0.06% in diesel), indicating better combustion due to ZnO's catalytic effect.

Overall, the results highlight that producing biodiesel from Used Cooking Oil is not only feasible but also environmentally friendly. It offers a promising alternative to traditional diesel while promoting circular economy practices by turning waste into valuable products.

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