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Innovative Approaches in Biodiesel Production from Waste Cooking Oils and Waste Animal Fats

Akash Phillip[1], Nandini Saini[1]
Department of Biotechnology, IIMT University, Uttar Pradesh, Meerut

Abstract: In the past few years, biodiesel has garnered considerable interest from researchers, government bodies, and industries as a sustainable, eco-friendly, and safe alternative fuel. Nonetheless, various feedstocks have been deemed impractical or unviable due to their exorbitant costs, primarily because they are utilized as food sources. Waste cooking oils (WCOs) and waste animal fats (WAFs) stand out as the most viable options for biodiesel feedstocks, despite their challenges, since treating such waste can be quite expensive due to stringent environmental regulations. A portion of these expenses might be mitigated through the production of bioenergy like biodiesel. This review article offers an extensive analysis of the pre-treatment processes and the application of WCOs and WAFs in biodiesel production. The predominant method for generating biodiesel is transesterification. Additionally, this paper emphasizes the purification and examination of the biodiesel produced, along with the latest innovations in biodiesel production from WCOs and WAFs. This review concludes that both WCOs and WAFs hold great potential as feedstocks for the production of biodiesel.
Keywords: Biodiesel, Transesterification, FAME (Fatty Acid Methyl Ester), Waste cooking oils (WCOs), waste animal fats (WAFs)

I. INTRODUCTION

Current global energy consumption heavily favors fossil fuels, comprising about 84.3% of usage, while renewables like wind and solar account for merely 3.3% despite substantial capacity [1]. This dependency is exacerbated by geopolitical issues, notably the energy crisis stemming from the Russian invasion of Ukraine, which has inflated fuel prices and exposed energy access vulnerabilities in developing countries [1]. With a growing and urbanizing global population, energy demand is expected to rise, necessitating a transition to sustainable energy solutions to address climate change and mitigate greenhouse gas emissions [2]. The COVID-19 pandemic has highlighted the necessity for resilient energy systems, leading to a reassessment of energy policies towards renewable sources [3]. Research demonstrates that integrating renewable energy can substantially reduce fossil fuel use and CO2 emissions, thereby fostering sustainability and economic advantages [4]. hus, the shift to renewable energy is essential for confronting existing consumption patterns and future energy requirements.

Utilizing biofuels like biodiesel offers significant environmental advantages over fossil fuels, particularly in emissions reduction and carbon footprint. Studies show biodiesel can lower harmful emissions, including greenhouse gases, by up to 86% versus petroleum diesel [5]. The use of WCOs and WAFs as biodiesel feedstocks presents notable benefits. These feedstocks are plentiful and readily available, promoting cost-effective production and efficient supply chains [6]. Additionally, sourcing biodiesel from these materials mitigates competition with food resources, enhancing sustainability [5], [7]. Employing WCOs also addresses disposal-related environmental issues, thus contributing to waste management [8]. Biodiesel from these sources is renewable and biodegradable, providing an eco-friendly alternative to fossil fuels while lowering greenhouse gas emissions [9]. Furthermore, biodiesel blends reduce noise emissions and enhance air quality, positively impacting human health [10]. Nonetheless, challenges like elevated nitrogen oxide (NOx) emissions and reduced thermal efficiency must be resolved for wider acceptance [11]. The transesterification process used to convert these oils into biodiesel is adaptable, allowing diverse catalysts to improve production efficiency [12], [13]. Additionally, employing heterogeneous catalysts from waste materials promotes recycling and sustainability in biodiesel production [13].

II. WASTE COOKING OILS (WCOS) AND WASTE ANIMAL FATS (WAFS) AS FEEDSTOCKS

The chemical composition of waste oils and fats critically determines their viability for biodiesel production [14] [15]. Essential parameters encompass triglycerides, free fatty acids (FFA), and total polar matter (TPM) [16]. WCOs exhibits low FFA levels, promoting biodiesel yield, as evidenced by an 85.3% yield from WCOs with an acid value of 1.09 mg KOH/g [17].

The transesterification process converting triglycerides to biodiesel is influenced by the oil's fatty acid composition and impurities like TPM, which may increase viscosity and affect engine performance [18]. Furthermore, heterogeneous catalysts sourced from waste materials have shown potential in improving biodiesel yield, achieving up to 95% yield with innovative catalysts [19]. Likewise, the ideal chemical makeup of WAFs for biodiesel production is contingent upon multiple critical factors, including catalyst type, reaction conditions, and feedstock ratios [20]. Studies indicate that waste animal fat combined with catalysts such as sulfuric acid (H_2SO_4) and potassium hydroxide (KOH) yields variable results; H_2SO_4, for instance, attained a biodiesel yield of 65.7% at optimized conditions of 60°C with a 5:1 methanol-to-oil ratio [21]. Additionally, research employing a CaO-based catalyst from agricultural waste achieved a maximum yield of 99.20% under specific conditions of 79.68°C and a catalyst proportion of 5.0% [22].

III. SOURCES OF WASTE COOKING OILS & ANIMAL FAT WASTE

WCOs and WAFs are derived from numerous sectors, each providing distinct categories of byproducts that can be utilized for the production of biodiesel.

A. Waste cooking oils and waste animal fats generated by Households

This category encompasses cooking oils such as sunflower, canola, and olive oils that are employed in domestic culinary practices to fry various food items [23]. Following multiple applications, these oils are frequently discarded. Accumulated grease (Residual Cooking Grease) originating from frying pans or roasting trays, commonly associated with the cooking of meats, can gather over time and is typically disposed of as waste [23]. Waste animal fats that are released during the preparation of meats such as pork, cattle, or poultry (for instance, bacon drippings, poultry fat) have the propensity to accumulate within domestic environments [24].

B. Waste cooking oils and waste animal fats generated by Restaurants

Dining establishments frequently employ substantial volumes of oil for the deep frying of various foods, including but not limited to French fries, poultry, and fish [25]. These oils are routinely replaced and disposed of as waste materials. Oils utilized in the grilling or pan-frying processes for foods such as hamburgers, steaks, or vegetables also contribute to the generation of waste oils [26]. Animal fats such as Tallow, this fats is predominantly derived from bovine or ovine sources, which emerge as a byproduct of culinary practices and food preparation in dining establishments, particularly those that focus on meat-centric dishes. Another example of WAFs from restaurants is Lard, which is a fat from pork, frequently employed in traditional culinary techniques, and has the potential to be classified as waste following the cooking process [27].

C. Waste cooking oils and waste animal fats generated from food processing industries

The production of fried snacks like chips or processed foods often generates large amounts of used oils, which are discarded after multiple batches as well as oils used in preserving or canning foods, such as vegetable oils used in canned fish, can contribute to waste once they are no longer usable [28]. Animal fat trimmings from meat processing plants are rendered into tallow or lard [29]. These fats, once rendered, may not be entirely utilized and are considered waste. Large-scale cooking operations in food processing may generate significant amounts of WAFs from cooking meats, which can be collected and used for biodiesel production [25].

IV. CONVERSION TECHNOLOGIES

A. Process of Transesterification

Transesterification is a chemical process used to convert fats and oils (triglycerides) into biodiesel and glycerol as illustrated in Fig. 1. This process is fundamental in biodiesel production and involves the reaction of triglycerides with an alcohol, typically methanol or ethanol, in the presence of a catalyst [30].

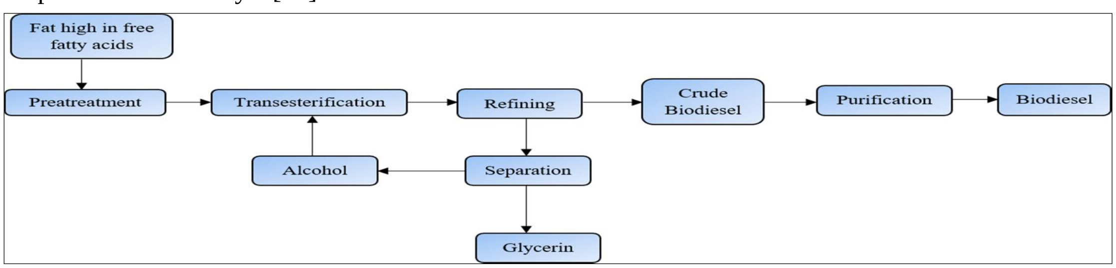

Fig. 1 Steps involved in the production of biodiesel through the process of transesterification.

- Mixing: The triglycerides (fats or oils) are mixed with the alcohol and the catalyst.
- Reaction/Transesterification: The alcohol reacts with the triglycerides, breaking the bonds between the glycerol and the fatty acids. This reaction results in the formation of fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE), which are the chemical names for biodiesel, and glycerol as a byproduct. The overall reaction can be simplified as shown in eq (1).

$$\text{Triglyceride} + 3\text{Alcohol} \rightarrow 3\text{Biodiesel} + \text{Glycerol} \qquad (1)$$

- Refining/Separation: Once the reaction is complete, the mixture is allowed to settle. Because biodiesel and glycerol have different densities, they naturally separate into two layers. Biodiesel, being less dense, forms the upper layer, while glycerol settles at the bottom.
- Purification: The separated biodiesel is then purified to remove any residual catalyst, alcohol, and other impurities. This typically involves washing with water and drying to ensure high-quality fuel.
- Glycerol Utilization: The glycerol byproduct can be further processed and purified for use in various industries, including pharmaceuticals, and cosmetics, and as a feedstock for other chemical processes.

B. Catalyst utilized in the process of transesterification

In the transesterification process used for biodiesel production, both acid and alkaline (base) catalysts play crucial roles. However, their suitability depends on the type of feedstock being used, particularly in terms of the free fatty acid (FFA) content [31].

1) Alkaline Catalysts (e.g., Sodium Hydroxide, Potassium Hydroxide):

Alkaline catalysts are generally faster in catalyzing the transesterification process. They are highly efficient at converting triglycerides to biodiesel under relatively mild conditions (lower temperatures and pressures). These catalysts are most suitable for feedstocks with low levels of free fatty acids (FFA), such as refined vegetable oils or used cooking oils that have been pre-treated to reduce FFA content [32].

Additionally,alkaline-catalyzed transesterification is carried out at lower temperatures (around 50-60°C) and requires less time to complete the reaction. However, they are sensitive to FFAs. When FFAs are present in significant amounts, they react with the alkaline catalyst to form soap, a process known as saponification. This reduces the yield of biodiesel and complicates the separation of biodiesel from glycerol, increasing processing costs and complexity [33].

2) Acid Catalysts (e.g., Sulfuric Acid, Hydrochloric Acid)

Acid catalysts are slower than alkaline catalysts in the transesterification reaction, requiring longer reaction times and higher temperatures (usually above 60°C). These catalysts are particularly effective for feedstocks with high free fatty acid content, such as waste animal fats, greases, or unrefined oils (e.g., crude palm oil). They can catalyze both the esterification of FFAs into esters and the transesterification of triglycerides, making them versatile in handling a broader range of feedstocks [32]. Additionally, acid-catalyzed reactions typically require more stringent conditions, including higher temperatures and longer reaction times, which can lead to higher energy consumption and costs. However, acid catalysts are not affected by the presence of FFAs. Instead of forming soap, they convert FFAs directly into biodiesel through esterification, which makes them ideal for feedstocks with high FFA content [34].

3) Nanocatalysts

Nanomaterial catalysts represent an innovative approach to enhancing the transesterification process in biodiesel production, overcoming traditional catalyst constraints [35]. Their elevated surface area and superior catalytic performance markedly enhance reaction efficiency, facilitating improved triglyceride conversion to fatty acid methyl esters (FAME) [36]. For example, barium oxide (BaO) nanoparticles have achieved a peak yield of 78.38% under optimized conditions, underscoring their efficacy as heterogeneous catalysts [37].

Moreover, advanced materials such as metal-organic frameworks (MOFs) and sulfonated carbon nanoparticles have been investigated, achieving over 90% conversion rates and streamlining industrial processes due to reduced operational demands [38]. Nevertheless, despite the benefits of these nanocatalysts, including reusability and diminished environmental impact, issues related to potential toxicity and the necessity for comprehensive studies on their long-term effects remain pressing. In conclusion, the adoption of nanomaterials in biodiesel production is promising for advancing sustainability and efficiency within the biofuel industry.

4) Homogeneous vs. Heterogeneous Catalysts

Homogeneous catalysts (liquid-based) typically offer faster reaction rates but are difficult to separate and reuse. Heterogeneous catalysts (solid-based), on the other hand, are easier to recover and recycle, but may have slower reaction kinetics. A comparision between homogeneous and heterogeneous catalysts is presented in the Table 1. Understanding these differences helps optimize catalyst selection based on the feedstock and production scale, improving both the economic and environmental performance of biodiesel production.

Table I A comparison between homogeneous and heterogeneous catalysts

Aspect	Homogeneous Catalysts (Liquid)	Heterogeneous Catalysts (Solid)	References
Reaction Efficiency	High, fast reaction rates	Lower, may require higher temperatures or longer times	[39], [40]
Separation and Purification	Difficult, requires additional steps	Easy, simple separation of solid catalyst	
Reusability	Limited, often single-use	High, can be reused multiple times	
Environmental Impact	Higher, requires neutralization or disposal	Lower, less waste and simpler disposal	
Corrosion	High, can cause equipment wear	Lower, less corrosive to equipment	
Cost	Lower initial cost, higher operational cost due to separation	Higher initial cost, lower operational cost due to reusability	
Commercial Adoption	Well-established, widely used	Emerging, less commercially adopted	

C. Supercritical transesterification

In supercritical transesterification, methanol or ethanol is used in its supercritical state to react with triglycerides in fats or oils, converting them into biodiesel (methyl or ethyl esters) and glycerol [41]. A fluid reaches a supercritical state when it is heated above its critical temperature and compressed above its critical pressure. Methanol becomes supercritical at a temperature of around 240°C and a pressure of about 8 MPa (80 bar) and ethanol becomes supercritical at a slightly higher temperature, around 243°C, and a pressure of about 6.4 MPa (64 bar) [42].

The triglyceride-containing feedstock (e.g., vegetable oil, animal fat) is preheated and mixed with methanol or ethanol, a high alcohol-to-oil ratio is typically used to drive the reaction toward complete conversion [43]. This mixture is then subjected to temperatures and pressures above the critical point of methanol or ethanol. This usually involves temperatures between 240°C and 350°C and pressures ranging from 8 MPa to 20 MPa [44]. Under these supercritical conditions, the methanol or ethanol dissolves the triglycerides, breaking them down into their constituent fatty acids and glycerol. The alcohol molecules then react with the fatty acids to form fatty acid esters (biodiesel) and glycerol. Unlike conventional methods, this process does not require a catalyst [45]. The reaction is typically rapid, often completing within minutes due to the enhanced solubility and reactivity of the supercritical alcohol. After the reaction, the pressure is released, and the reaction mixture is cooled. Biodiesel is separated from glycerol and any unreacted methanol or ethanol, which can be recovered and recycled back into the process [46].

D. Enzymatic transesterification

Enzymatic transesterification uses enzymes, specifically *lipases*, to catalyze the conversion of triglycerides (fats and oils) into biodiesel (fatty acid methyl esters or FAME) and glycerol [47].

The triglyceride-containing feedstock is mixed with an alcohol (methanol or ethanol) and the lipase enzyme. In some processes, the enzyme is immobilized on a solid support, allowing it to be easily separated and reused [48]. The enzyme catalyzes two main reactions:

- Hydrolysis: The lipase first hydrolyzes the triglycerides into free fatty acids and glycerol.
- Esterification/Transesterification: The free fatty acids react with the alcohol to form biodiesel and water, while the remaining diglycerides and monoglycerides are transesterified to form additional biodiesel and glycerol.

The reaction typically occurs under mild conditions, such as temperatures ranging from 30°C to 60°C, which is significantly lower than the conditions required for chemical catalysis. After the reaction, the mixture is separated. Biodiesel is collected, and the byproducts (glycerol and water) are removed. If an immobilized enzyme is used, it can be filtered out and reused for subsequent batches. The biodiesel may require minimal purification due to the absence of catalysts, reducing the need for extensive washing or neutralization steps [49].

V. TECHNIQUES FOR ENHANCING BIODIESEL PRODUCTION

A. Feedstock pretreatment

Feedstock pretreatment represents an essential phase in the process of biodiesel production, particularly when employing waste oils and fats as feed materials. These feedstocks frequently harbor impurities such as moisture, free fatty acids (FFAs), solid particulates, and various other contaminants that have the potential to detrimentally influence the efficiency and yield of the transesterification reaction [50] as presented in Table 2. Adequate pretreatment serves to ascertain that the feedstock meets the requisite quality standards for biodiesel production, thereby mitigating the likelihood of complications such as soap formation, catalyst deactivation, and suboptimal product quality [51].

Table II Different techniques for the pretreatment of waste oils and fats

Impurity	Pretreatment Technique	Purpose	Method	Applications	References
Solid Particles	Filtration	Remove solid particles and debris	Passing oil through filters of varying mesh sizes	Waste cooking oils, waste animal fats with solid impurities	[51], [52], [53]
Water (Free Water)	Settling and Decantation	Separate free water and heavy solids	Allow oil to settle; decant or siphon off the top layer	Waste oils and fats containing free water and large particles	
Fine Solids, Water	Centrifugation	Remove fine solids, water, and emulsified impurities	Spinning oil at high speed to separate impurities	More thorough separation when higher purification is required	
Phospholipids (Gums)	Degumming	Remove phospholipids that interfere with transesterification	Adding water or acid to precipitate gums; filtration/centrifugation	Vegetable oils with high phospholipid content (e.g., soybean)	
Water-Soluble Impurities	Water Washing	Remove water-soluble impurities, salts, and some FFAs	Mixing oil with warm water; separating oil from water layer	Reducing polar impurities; must avoid residual water in oil	
Residual Water	Drying (Dehydration)	Remove residual water that can inhibit transesterification	Heating under vacuum or at moderate temperature; chemical drying agents	Necessary after water washing or when feedstock has absorbed moisture	
Free Fatty Acids (FFAs)	Acid Pretreatment (Esterification)	Reduce FFAs by converting them into biodiesel precursors	Treating with acid catalyst and alcohol to esterify FFAs	Feedstocks with high FFA content (e.g., waste animal fats, waste grease)	
Residual Water	Drying (Dehydration)	Remove residual water that can inhibit transesterification	Heating under vacuum or at moderate temperature; chemical drying agents	Necessary after water washing or when feedstock has absorbed moisture	

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B. *Process Optimization*

1) *Reaction conditions for the efficient production of biodiesel*

In order to maximize yield and quality, certain reaction conditions are necessary for efficient biodiesel manufacturing. The impact of various reaction conditions and the ideal parameters for effective biodiesel generation are explained in Table 3.

Table III The influence of reaction conditions on biodiesel production efficiency

Parameter	Impact on Biodiesel Yield and Quality	Optimal Range/Considerations	References
Temperature	Higher temperatures increase the reaction rate by enhancing molecular interactions, leading to faster transesterification. Optimal temperatures can maximize biodiesel yield by driving the reaction to completion. Excessively high temperatures can cause unwanted side reactions, such as the formation of soap (especially with alkaline catalysts), or thermal degradation of biodiesel, reducing its quality.	Typically between 50°C and 65°C, depending on the feedstock and catalyst used. Temperatures above 65°C may lead to evaporation of alcohol (methanol or ethanol) and increased soap formation in alkaline-catalyzed processes.	[54], [55], [56]
Pressure	In conventional transesterification, atmospheric pressure is usually sufficient, but in supercritical transesterification, high pressures are necessary to maintain the alcohol in a supercritical state. High pressure, particularly in supercritical processes, enhances the solubility of alcohol in oil, improving yield. High pressure can help prevent the formation of soap and other side reactions by maintaining the alcohol in a supercritical state, leading to a cleaner reaction and higher biodiesel purity.	For conventional processes: Atmospheric pressure. For supercritical transesterification: 8 MPa to 20 MPa. High pressure is particularly important in supercritical methanol or ethanol transesterification, where it helps achieve high yield and quality without the need for a catalyst.	
Catalyst Concentration	Sufficient catalyst concentration is needed to initiate and sustain the transesterification reaction. Too little catalyst may result in incomplete conversion, lowering biodiesel yield, while too much can lead to excessive soap formation (in alkaline-catalyzed reactions), complicating separation and purification. Optimal catalyst concentration ensures high conversion of triglycerides to biodiesel while minimizing side reactions that can degrade quality.	Typically, 0.5% to 1% weight of the oil for alkaline catalysts (e.g., sodium hydroxide, potassium hydroxide). The optimal concentration depends on the feedstock quality (e.g., FFA content) and the type of catalyst. Acid catalysts (e.g., sulfuric acid) may require different concentrations, particularly in pretreatment steps. Careful balance is needed to maximize yield without compromising biodiesel quality.	

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C. Emerging Technologies

1) Utilizing Biochar as a Catalyst for Biodiesel Production

Biochar, which is rich in carbon and is a byproduct of pyrolysis, is being investigated as a catalyst for producing biodiesel. It is highly appreciated for its extensive surface area, excellent porosity, and capacity to absorb impurities [57]. Scientists have created catalysts supported by biochar, such as biochar infused with metal oxides (e.g., CaO-biochar), which have demonstrated potential in catalyzing the conversion of waste oils into biodiesel [58]. These catalysts can be used again and are eco-friendly, which helps decrease the total expenses and waste linked to the procedure. Using biochar not only reuses biomass waste but also improves biodiesel production efficiency by supplying a steady, inexpensive catalyst [59].

2) Genetically Engineered Microorganisms for Biodiesel Production

Researchers are investigating genetically modified microorganisms for their capacity to effectively transform waste oils into biodiesel using enzymatic transesterification methods [60]. Modified strains of E. coli have been developed by researchers to produce lipase enzymes that can convert waste oils into biodiesel without any intermediate steps [61]. These genetically modified bacteria can carry out the complete transformation at low temperatures, minimizing the reliance on outside chemical catalysts and significant energy requirements [62]. Microbial catalysis provides a specialized and effective method of converting substances, which could reduce production expenses and energy needs. These systems have the potential to be expanded for use in industrial settings, providing a sustainable and renewable method for producing biodiesel [63].

VI. CHALLENGES IN BIODIESEL PRODUCTION

Various technical obstacles can affect the efficiency, yield, and overall sustainability of the biodiesel production process. Important concerns include variations in feedstock, loss of activity in the catalyst, and increasing the size of the process [64].

A. Feedstock variability

This variation may occur because of the utilization of various feedstocks (such as vegetable oils, WAFs, and WCOs) and variations in purity, free fatty acid (FFA) levels, moisture content, and impurity presence. Various raw materials have different amounts of FFAs, water content, and impurities, all of which can impact how well the transesterification process works. Elevated FFA levels, for instance, may result in the production of soap, which can decrease biodiesel output and make product separation more difficult. Differences in raw materials can result in variations in the ultimate quality of biodiesel, impacting characteristics like viscosity, cetane number, and cloud point [65].

B. Catalyst Deactivation

Catalyst deactivation happens when the effectiveness of a catalyst diminishes with time, decreasing its capability to aid the transesterification reaction. This might result from physical, chemical, or thermal causes. Impurities in feedstock like water, free fatty acids, and metal ions can render the catalyst inactive or harmful. Extended exposure to elevated temperatures can result in catalyst degradation, particularly in ongoing processes. A build-up of waste materials or unused raw materials on the catalyst's surface can obstruct active sites, leading to decreased catalyst effectiveness [65].

Deactivation causes a reduction in the efficiency of triglyceride conversion to biodiesel, leading to decreased yields and more waste. Additional catalysts might be necessary to reach the desired speed of the reaction, which could raise operating expenses and possibly result in more instances of side reactions such as the creation of soap. Regularly changing catalysts, particularly costly options such as heterogeneous or enzymatic ones, can lead to higher overall expenses in production [66].

C. Process Scaling

Process scaling involves overcoming difficulties that come with expanding the output capability of a biodiesel plant, and transitioning from smaller-scale testing to large-scale manufacturing. Enlarging the scale can result in challenges in upholding consistent reaction conditions (such as temperature, mixing, and catalyst concentration), impacting the uniformity of the product and its yield. Inadequate heat and mass transfer in bigger reactors can cause incomplete reactions or hot spots, resulting in decreased efficiency and potential safety problems. Expanding typically involves investing in bigger or more sophisticated machinery and making changes to infrastructure like storage and handling systems, which can be expensive and complicated [66].

VII. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

Using WCOs and WAFs for biodiesel production offers significant environmental benefits, particularly in reducing waste and greenhouse gas emissions compared to conventional fossil fuels [67].

A. *Waste Reduction*

Redirecting waste oils and fats away from landfills decreases the space required for waste disposal, thereby reducing the environmental impact of waste management. Avoiding dumping oils and fats in sewage systems prevents blockages and decreases the chance of water pollution, which can negatively impact aquatic animals and disrupt water treatment procedures. Biodiesel production reduces the need for new feedstocks by repurposing waste materials, supporting the principles of a circular economy and efficient resource utilization [68].

B. *Greenhouse Gas Emissions Reduction*

The combustion of biodiesel leads to reduced net CO_2 emissions due to the use of feedstocks from biological sources that absorb CO_2 as they grow, balancing out the emissions released when the fuel is combusted. If not used, waste oils and fats can break down without oxygen in landfills, producing methane, a strong greenhouse gas. Transforming these resources into biodiesel rather than letting them decompose greatly decreases the amount of methane released into the environment. Biodiesel made from waste feedstocks plays a role in reducing carbon emissions to aid in achieving global and national goals in combating climate change [69].

C. *Reducing our dependence on fossil fuels*

Adding biodiesel to the energy mix decreases dependence on fossil fuels and helps create a more sustainable and robust energy system. A decline in the need for fossil fuels can result in lower environmental effects linked to their extraction, like habitat loss, water pollution, and air pollution caused by drilling and mining operations [70].

D. *Cost analysis of using waste oils and fats versus virgin feedstocks*

Recycled oils and fats are generally priced between \$0.10 and \$0.30 per liter, much more affordable than new oils such as soybean or palm oil, which are priced at around \$0.70 to \$1.00 per liter. The cost fluctuates depending on worldwide market factors, sometimes resulting in higher prices and reduced economic viability for large-scale biodiesel manufacturing [71].

Additional processing such as filtration and degumming is often necessary for waste oils to eliminate impurities such as free fatty acids and water content. Yet, the increased processing expenses are frequently balanced out by the inexpensive waste feedstocks. The cost of the transesterification process is consistent whether utilizing waste or virgin feedstocks, as triglycerides in oils react with methanol or ethanol [72]. Nevertheless, the higher FFA content in waste oils may require acid catalysts, leading to a slight increase in expenses.

Numerous governments offer financial assistance or tax breaks for producing biodiesel, especially when using leftover feedstocks. The Biodiesel Mixture Excise Tax Credit in the United States provides \$1.00 for every gallon of biodiesel mixed with petroleum diesel. Producers who use waste oils may take advantage of carbon credits or other incentives that are designed to lower greenhouse gas emissions, thus enhancing the economic viability [73].

Research indicates that producing biodiesel from waste oils can cost 30-50% less than using virgin oils. Biodiesel derived from waste oils costs approximately \$0.40 to \$0.70 per liter, whereas virgin oil biodiesel is priced between \$1.00 and \$1.20 per liter. Current data shows that waste oils make up around 30-40% of the feedstock used for global biodiesel production, thanks to their cost-effectiveness and environmental advantages [74].

VIII. CONCLUSION

Overall, the chemical characteristics of waste oils, including their triglyceride content and FFA levels, are critical in determining their viability as biodiesel feedstocks. Overall, the optimal composition appears to be a blend of animal fat with effective catalysts and carefully controlled reaction parameters to maximize yield and efficiency. Furthermore, the use of WCO and WAF blends has shown promising results, with biodiesel yields reaching up to 92.34% when optimized for methanol-to-oil ratios and catalyst weight. Additionally, using waste oils and animal fat for biodiesel production offers substantial environmental benefits, including waste reduction, lower greenhouse gas emissions, reduced reliance on fossil fuels, and improved air quality. Collectively, these elements highlight the potential of WCOs and WAFs in propelling biodiesel as a feasible energy source.

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X. CONFLICT OF INTEREST

The authors confirms that the manuscript was written without any involvement from a financial agency.

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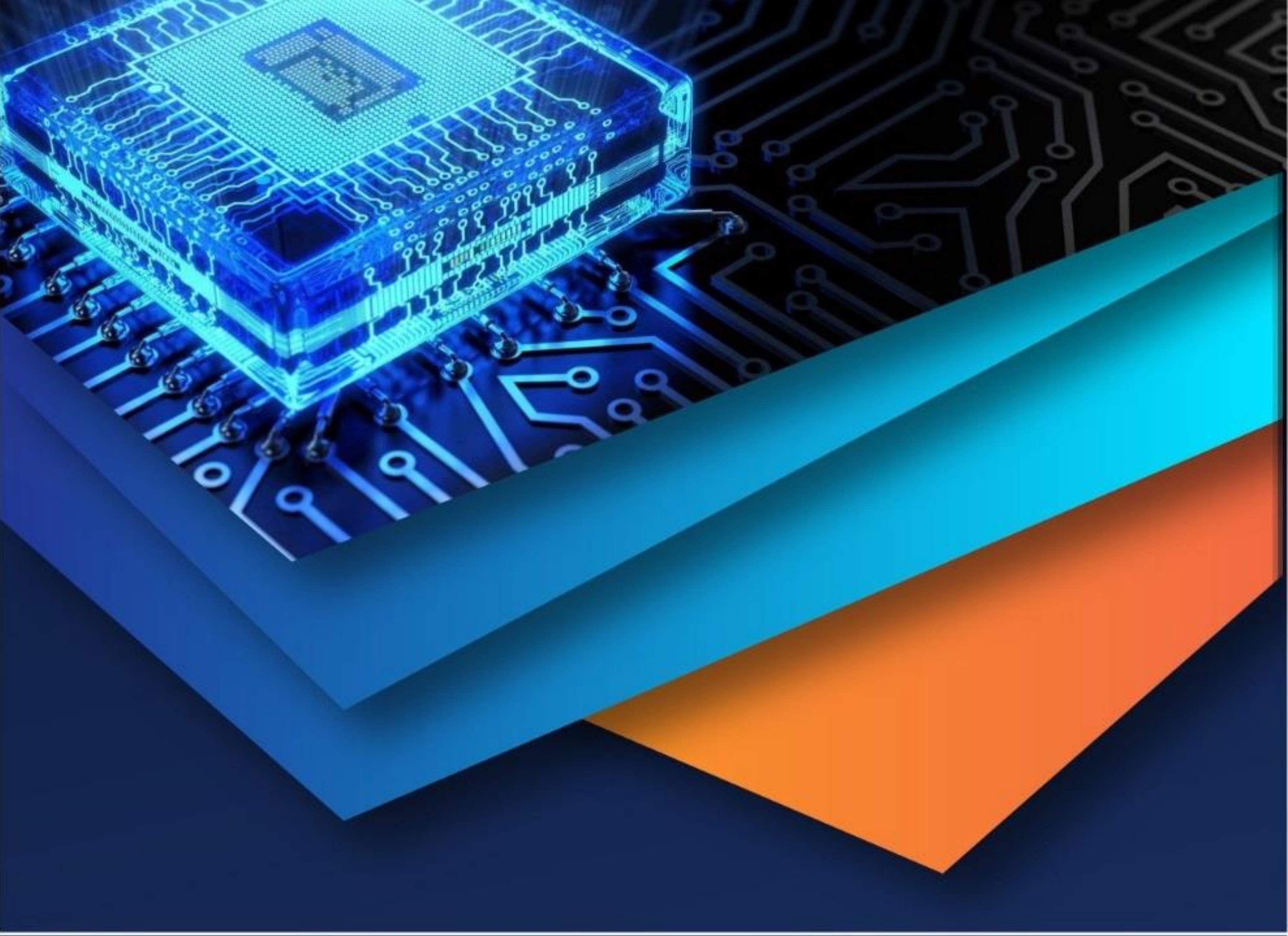

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