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Biodiesel Production from Waste Cooking Oil: A Review of Prospects and Challenges

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ABSTRACT

The consumption of fossil fuels is increasing as people become more reliant on them. It is consequently vital to discover more environmentally friendly and sustainable alternative energy sources. Because of its considerable potential to reduce greenhouse gas emissions and its renewable nature, biodiesel derived from WCO has gained attention as a feasible alternative. Enhancing product quality and guaranteeing consistent economic growth are substantial challenges. This investigation aims to assess the feasibility of utilizing WCO as a renewable resource to produce biodiesel. In particular, the investigation investigates the feasibility of obtaining cost-effective and high-quality biodiesel results. To optimize outcomes, this investigation implements a transesterification approach that employs calcium oxide catalysts. Biodiesel's economic value and environmental benefits are assessed through the Life Cycle Cost Assessment (LCCA) assessment method. WCO biodiesel exhibits a high conversion rate and favorable physicochemical properties, as indicated by the results. Therefore, WCO biodiesel can meet the worldwide demand for fuel. The results show that WCO biodiesel has favorable physicochemical properties and a high conversion rate. As a result, WCO biodiesel can meet global fuel demand. It has the potential to generate many benefits for the environment, but there are problems with the collection and processing of WCO. However, WCO collection and processing issues still exist. Biodiesel derived from WCO reduces harmful pollutants, improves public health and air purity, according to engine performance tests.

1. Introduction

Biodiesel as a renewable source of energy gives important solutions to the global energy crisis [1,2]. There has been an increase in diesel fuel consumption, which has risen over time from 3.5 million metric tons in 2010 to 3.9 million metric tons in 2019 [3]. The ever-growing need in this case keeps on insinuating that there should be an environmentally friendly and ecologically sound solution, which biofuel offers. From the above, the use of biodiesel can be seen to be very promising

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in this case being quite a viable replacement for petroleum-based diesel fuel [4-11]. As such, the biodiesel produced from these sources of vegetables is environmentally friendly and possesses many beneficial characteristics [12,13].

Biodiesel fuels effectively reduce environmental hazards compared to fossil fuels when produced from renewable sources like vegetable oils, animal fats, and recovered grease [14-18]. However, the production and use of the same cause major reductions in greenhouse gas emissions, which is the most characteristic cause of climate change [19,20]. This lessening is largely attributed to the closed carbon cycle of biodiesel [21]. The plants then take up the carbon dioxide emissions from burning biodiesel, utilized in further biodiesel production, thus establishing a balance in the carbon cycle [22-27]. Other enormous benefits of biodiesel involve its capability of biodegradation [28,29]. Biodiesel has very simple hydrocarbon chains that can biodegrade in the environment at a faster, harmless pace [30]. Moreover, its non-toxic nature reduces potential harm to human health and ecosystems, increasing the reputation of biodiesel as a green fuel choice [31]. In addition, the fact that biodiesel is compatible with current diesel engines provides important logistical benefits [32,33]. Biodiesel can be used in vehicles and engines currently operating on diesel fuel and does not need more modifications. This factor is especially important for commercial and industrial transportation which relies heavily on diesel engines, as it allows for gradual shifting without requiring significant start-up capital [34-36].

The growing interest in biodiesel is being witnessed across the world from an environmental point of view and strategic energy security considerations [37,38]. Biodiesel is sourced from renewable sources such as algae and waste oil; it is a cleaner option than traditional fossil fuels and reduces greenhouse gas emissions by up to 86% [39]. Studies have demonstrated that using WCO biodiesel can lead to significant reductions in CO emissions, with some reports indicating reductions of up to 78% compared to conventional diesel [40]. Moreover, various regions have successfully implemented WCO biodiesel, demonstrating improved air quality and energy security benefits. Thus, this gradual shift to biodiesel is motivated by caring for environmental problems, be they those caused by the consumption of fossil fuel, guaranteeing energy about fluctuations in crude oil prices and energy insecurity, or ensuring that energy is used efficiently. Local biodiesel production from diversified feedstocks reduces dependency on imported oil and thus enhances national energy security and provides economic benefits like job creation in the green energy industry [41-44].

Biodiesel offers significant environmental benefits and is compatible with existing diesel engines [45]. It is a renewable low-carbon fuel source, with the potential to lower greenhouse gases, improve air quality, and further increase energy independence [46,47]. The production of cleaner fuel, biodiesel, from organic sources like vegetable oils and WCO emits lower lifecycle greenhouse gas emissions compared to petroleum diesel [48-50]. Some more studies report that biodiesel is usable in the unmodified diesel engine [51]. Further improvement in engine performance and reduction in emissions can be achieved through the addition of oxygenated additives like diethyl ether [52,53]. Moreover, a test made in diesel engines has shown that biodiesel derived from oil microalgae has improved combustion properties and low emissions of such harmful pollutants as hydrocarbons, carbon monoxide, and others [54-56]. Another study showed that under high engine rpm, the engine performance results of bio-diesel mixtures exhibited almost similar behavior to diesel fuel with appreciable reductions in the emission levels of carbon monoxide (33.3%), hydrocarbons (33.3 to 73.3%), and particulate matter (17.8 to 28.8%) [57].

Recent studies have shown that heterogeneous chromatography has significant promise for reducing toxicity in WCO transesterification, as compared to homogeneous chromatography [58]. However, in order to optimize biodiesel production, it is necessary to address the limitations and risks that persist, despite the efficacy of CaO and other chromatographic techniques. Catalysis is crucial for biodiesel generation, with CaO yielding high biodiesel under favorable conditions [59]. However, performance is influenced by chromatography and time-reactive chromatography. CaO enhances stability and efficiency, but requires more complex processing [60]. Selecting the right catalyst depends on the biodiesel production process's specific requirements. Comparing performance indicators like biodiesel yield, reaction time, energy consumption, and environmental impact is crucial for understanding the effectiveness of optimization techniques [61]. For instance, a study using CaO catalyst yielded 96.53% with optimal concentration, methanol-to-oil ratio, and reaction temperature, while a CaO/ mesoporous silica catalyst yielded slightly lower but improved reusability and stability [62].

Despite notable advancements in the manufacture of biodiesel from several renewable sources, particularly WCO, there are crucial obstacles that must be resolved to enhance its consumption and optimize output [63,64]. Most of the research primarily concentrates on enhancing the physicochemical characteristics and economic viability of biodiesel derived from WCO [65]. However, there is limited research on comprehensive economic assessments across the entire life cycle of WCO biodiesel production and the environment, including collection, pretreatment, and their impact on engine performance under diverse real-world operating conditions. Furthermore, the potential for WCO biodiesel to expand in the global energy market and the implementation of effective regulatory frameworks and market mechanisms to promote its adoption have not been thoroughly investigated [66]. To fully harness the promise of WCO biodiesel as a sustainable alternative to fossil fuels, it is crucial to address this gap. This gap underscores the necessity for additional research that surpasses the technical elements of biodiesel production, placing emphasis on the significance of life cycle assessment, policy integration, and practical applications in various situations.

2. Raw Material

A wide range of feedstocks can be used in biodiesel production. First-generation feedstocks of vegetable oils include Jatropha oil, Neem oil, and Karanja oil [67,68]. Such second-generation raw materials may comprise inedible oils, waste vegetable oils, industrial by-products, animal fat, and lipids from microorganisms and insects [69,70]. In addition, glycerol, as one of the by-products of transesterification, may be refined into various industries as high-quality glycerin. Its utilization may be expanded to be used as a renewable feedstock to produce biofuels and chemicals [71]. Jatropha curcas, sunflower, and soybean are among the other plants that act as sources of biodiesel production [72]. Except for these, there are some other feedstocks, too, which can be used for biodiesel production. They include vegetable oils and animal fats [73]. Vegetable oils, though commonly used, raised concerns over rising prices, fueling interest in alternatives such as animal fat waste and meat industry by-products that are more sustainable and cheaper [74]. WCO has emerged as a promising feedstock for sustainable biodiesel production, offering high potential to meet energy demand while reducing environmental impact [64,75]. WCO is another viable source, especially when coupled with lime-based zinc-doped calcium oxide (Zn-CaO) catalysts for efficient biodiesel synthesis [76]. Halim *et al.,* [77] found Singora tiles modified with ZnO as a heterogeneous catalyst for the biodiesel transesterification process from WCO which produces 96.96% biodiesel. In addition, non-food feedstocks such as vegetable waste oils are increasingly being considered to alleviate food shortage concerns associated with the use of crops such as oil palm fruit for biofuel production [78].

2.1 Waste Cooking Oil (WCO)

Research on the utilization of WCO for biodiesel production has seen considerable growth, especially in Asian countries such as Indonesia, Malaysia, Taiwan, and China, which a major producers and consumers of palm oil [79]. Studies have focused on optimizing production techniques to increase biodiesel yields using cost-effective feedstocks such as waste oil and fats [80]. Attempts have been made to convert WCO into biofuel fractions using catalysts such as cobalt aluminate nanoparticles, achieving high conversion rates exceeding 90% [81,82]. In addition, the reuse of WCO through fermentation processes has been explored to produce free fatty acids, contributing to a circular economy by reducing environmental pollution [83,84].

Historical data from previous studies pay more attention to the potential of WCO as biodiesel feedstock in various countries. Studies have shown that WCO can be efficiently converted into biodiesel using solid acid catalysts such as SO42—/ZNO-β-zeolite [85]. In addition, WCO management through recycling pathways to produce biodiesel, bio-lubricants, and biosurfactants has been explored, emphasizing environmental sustainability and economic viability [86]. Furthermore, the catalytic performance of supported potassium hydroxide on alumina for WCO transesterification has been investigated, achieving a biodiesel yield of 86.6% under optimized reaction conditions [87]. Comparatively, biodiesel production from WCO and Palm Carnel Oil (PCO) has been evaluated, with PKO showing higher biodiesel yields and better characteristics, making it a promising alternative fuel [88]. These studies collectively demonstrate the potential of WCO as a sustainable feedstock for biodiesel production in countries such as China, Taiwan, Indonesia, and Malaysia.

Figure 1 shows a comparison of annual WCO production between China, Indonesia, Malaysia, and Taiwan, providing a clear picture of the difference in production scale in the region. China's significant production of 5 million tons of WCO per year, Chen *et al.,* [89] demonstrates its substantial potential to develop the WCO-based biodiesel industry. Various studies highlight the feasibility of utilizing WCO for biodiesel production, emphasizing environmental benefits and efficiency. Research has explored different catalysts such as zeolite synthesized from fly ash, lime-based zinc-doped calcium oxide (Zn-CaO), and the enzyme lipase immobilization on $CaCO_3$ for transesterification reactions, achieve high biodiesel yields, and meet fuel standards [90-92]. In addition, the systematic review emphasized the importance of enablers such as government policies, financial support, and technological advances in promoting WCO-based biodiesel production [93].

Indonesia, with production of 0.9 million tons per year, shows lower capacity compared to China, but still significant, considering the country's economy and population [94]. As an archipelagic country with a variety of food industries, Indonesia has the potential to optimize the use of WCO in renewable energy production [85]. Malaysia, with a reported production of 0.54 million tons per annum, also shows active participation in the biodiesel market [95,96]. With a thriving palm oil sector and government initiatives supporting the conversion of WCO to biodiesel, the country has set a strong foothold in its renewable energy roadmap. Taiwan, whose production data ranges from 0.03 to 0.05 million tons per year, may reflect a smaller scale of production but should not be underestimated [97]. The integration of WCO in national energy systems presents promising solutions for sustainable biodiesel production, addressing environmental issues and promoting renewable energy [93,98,99].

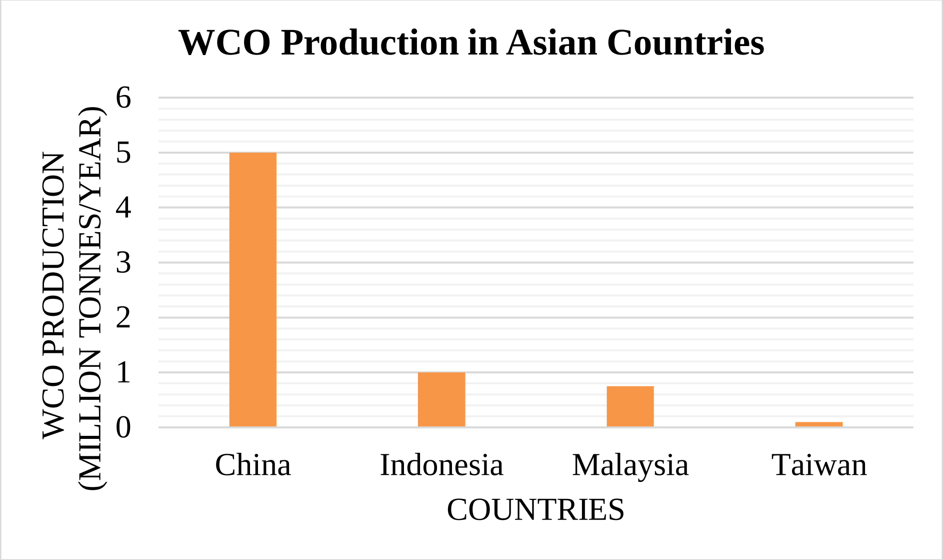

Fig. 1. WCO is produced in Asian countries

2.2 Research on Biodiesel from WCO

Studies have optimized esterification-transesterification reactions using a face-cantered central composite design model, determining optimal conditions for methanol-to-oil ratio, catalyst concentration, and reaction temperature [100]. Furthermore, investigations have highlighted the viability of WCO as a biodiesel feedstock, emphasizing its impact on health, income-generating potential, and environmental benefits [101]. Process optimization studies have shown that biodiesel yield increases with the ratio of specific methanol to oil and catalyst concentration [102]. Figure 2 shows a visualization of a keyword network describing the WCO thematic landscape. Research has extensively delved into the technical aspects of converting WCO into biodiesel.

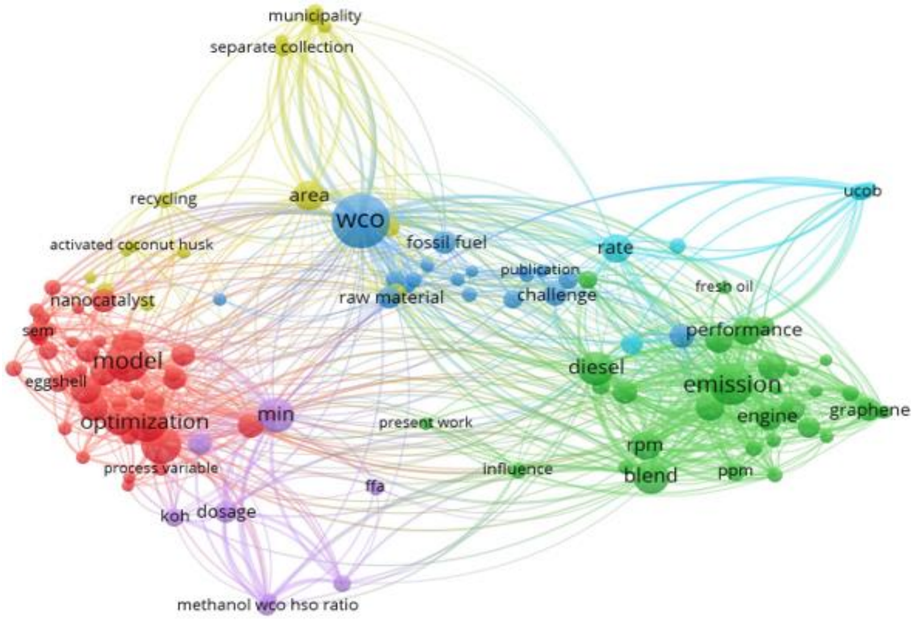

Fig. 2. WCO research on biodiesel from WCO

In addition, research has focused on the performance, emission characteristics, and combustion properties of biodiesel derived from WCO, exploring optimization parameters such as molar ratio, catalyst concentration, reaction conditions, and catalyst reusability [103]. Physicochemical evaluation has also been carried out to assess the feasibility of WCO as biodiesel feedstock after the purification process [104]. In WCO's research landscape analysis, visualization of this keyword network reveals diverse thematic groups, each of which represents a different research focus [105,106]. The keyword "WCO" is located at the center of the network, signifying as the main subject connecting various subtopics in the study [107,108]. This reflects the relevance of WCO as an important research topic, especially in discussions regarding alternative energy sources and sustainable waste management.

Subtopics related to 'WCO' include "fossil fuel”, “raw material”, and “diesel”, demonstrating the close relationship between WCO and the replacement of traditional fossil fuels [85,109,110]. This indicates significant exploration of WCO's potential as a sustainable substitute, motivating further studies in biodiesel fuel processing technology and performance. Keyword groups such as “emission”, “engine”, and 'performance' are closely related to 'diesel' and 'fossil fuel', which describe areas of research in combustion efficiency and emission characteristics of WCO-based biodiesel [111-114]. This confirms the importance of understanding the environmental impact of using WCO, not only in the context of its use as a fuel but also in engine performance and emission expenditure. In addition, concepts such as "nanocatalyst", “optimization”, and 'model' were placed in one group, indicating research focused on improving the biodiesel production process. The use of nanocatalysts and process modeling may be innovative approaches in recent research aimed at improving the efficiency and effectiveness of biodiesel production from WCO.

The existence of keywords such as “'municipality'” and separate collection” highlights aspects of waste management and WCO collection systems at the municipal level, which is important for infrastructure development that supports WCO processing into biodiesel [74,85,92]. Analysis of the research landscape represented by this network of keywords can guide researchers to identify gaps in the literature, suggest new directions for exploration, and develop advanced studies that will contribute to the field of sustainable biodiesel. Thus, the conclusions and recommendations drawn from this analysis have the potential to add value to our understanding of current research and future development in the use of WCO for biodiesel production.

Building upon the foundational understanding of waste management and the importance of infrastructure in WCO processing, it becomes crucial to explore advanced optimization techniques like Face-Centered Central Composite Design (FCCCD), which plays a pivotal role in refining the processes involved in biodiesel production. The Face-Centered Central Composite Design (FCCCD) is a modified version of the Central Composite Design (CCD), commonly employed in Response Surface Methodology (RSM) to optimize processes [115]. FCCCD is particularly notable for its application in experimental designs where the goal is to develop a quadratic model that can predict responses based on various input variables [116]. Unlike the standard CCD, FCCCD places all star points (or axial points) on the face of the cube, ensuring that all factors are evaluated at three levels: low (-1), center (0), and high (+1) [117]. In the context of biodiesel production, FCCCD serves as an essential tool for determining the optimal conditions necessary to maximize yield or improve the quality of biodiesel [118]. For example, in the study of $NaAlO_2/CuFe_2O_4$ as a catalyst for biodiesel synthesis, FCCCD was employed to evaluate and optimize four critical factors: reaction temperature, methanol to oil molar ratio, catalyst dosage, and reaction time [119]. By systematically varying these factors, the researchers were able to construct a predictive model that accurately described the relationship between these variables and the ester content of the biodiesel produced [120].

The comprehensive advantage of using FCCCD lies in its ability to assess both linear and interaction effects between variables while also considering potential curvature in the response surface [121]. This makes FCCCD particularly useful in situations where the underlying relationship between the variables is complex and nonlinear [122]. Additionally, the face-centered approach ensures that all experimental runs remain within the practical range of the factors, avoiding the extreme levels that may not be feasible or safe in real-world applications [123].

In summary, FCCCD is a robust and efficient experimental design methodology that enhances the reliability of process optimization studies. Its application in biodiesel production research exemplifies its value in fine-tuning the conditions to achieve maximum efficiency, ultimately contributing to the development of sustainable energy solutions [124].

2.3 Ecological Consequences

The utilization of WCO as biodiesel can indeed help in preserving the environment [125,126]. Improper disposal of WCO can cause adverse effects on soil and water quality. When WCO is discharged into the ground, it can contribute to soil hardening. Conversely, if WCO is released into water bodies, it can cause water pollution. Utilization of biodiesel fuel derived from WCO can reduce CO, H_2S, and NOx emissions [127,128]. The WCO biodiesel mixture has shown improved combustion characteristics, leading to lower CO and NOx emissions compared to conventional diesel fuel [129]. According to previous study who has been conducted by Fareed *et al.,* [130] study, the use of WB10, CB10, WB10+CB10, WB20, and CB20 biodiesel will reduce CO Emissions by 0.5%, 1.5%, 2.5%, 3%, and 3.5% respectively. On the other hand, the use of biodiesel made from WCO and castor oil has significant potential to be used as an alternative fuel in diesel engines. Environmental assessments reveal that WCO-based biodiesel has a lower endpoint impact on human health, ecosystem quality, and resource availability than fossil diesel. Table 1 presents a comparison of environmental and economic aspects between biodiesel vs conventional diesel.

Table 1
Comparison of environmental and economic aspects of biodiesel derived from WCO and conventional diesel

Aspect	Biodiesel from WCO	Conventional Diesel	Ref.
CO_2 Emissions	Lower due to renewable nature	Higher due to fossil fuel origin	Padder *et al.,* [131]
Production Cost	Generally lower, as WCO is a cheaper feedstock	Influenced by the global oil market, potentially higher	Mohadesi *et al.,* [132]
Waste Reduction	Significantly contributes to waste management	Not applicable	Nirmala *et al.,* [133] Ming *et al.,* [134]
Reduction of SO_2 Emissions	Reduction in SO_2 emissions due to lower sulphur content	Higher emissions due to higher sulphur content	Wang *et al.,* [135]
Sulphur Content	Lower sulphur content	Higher sulphur content depending on source and refining	Gebremariam and Marchetti [136] Mohadesi *et al.,* [137] Hazrat *et al.,* [138]

Biodiesel derived from WCO offers significant environmental advantages over conventional diesel. Studies demonstrate that WCO biodiesel reduces NO_x emissions by 2.1% while slightly increasing CO emissions by 19.8%, highlighting the need for engine optimization to balance these effects. Moreover, WCO biodiesel significantly lowers SO_2 emissions due to its lower sulfur content, contributing to improved air quality. Comparative analysis reveals that WCO biodiesel not only improves engine performance by 7.4%, but also plays a vital role in waste management by repurposing used cooking oil. However, the increased CO emissions temper the environmental benefits, underscoring the importance of advanced real-time monitoring and optimization techniques such as the Decision Elman Neural Framework (DENF). This data underscores WCO biodiesel's potential as a more sustainable alternative to conventional diesel, especially when coupled with advanced technologies to mitigate trade-offs.

2.4 Global Production and Consumption of Biodiesel

In the last ten years, there has been a sharp increase in biodiesel production from around 4% to 14%, bringing economic benefits with growing demand [139]. Figure 3 shows biodiesel production in geographic dispersion for 2021, which is 42.7 billion liters [140]. From this picture, Europe leads in biodiesel production with the highest percentage of 34% in the world. Biodiesel production, from 2023 to 2027, will increase to 50 to 52.5 billion liters respectively [141]. Figure 3 shows the amount of biodiesel consumption for 2021. It goes on to tell us that also on the percentage of biodiesel consumption, Europe has a high percentage of 35, with some of the lowest consumers being Canada and Mexico, both at 1.4%.

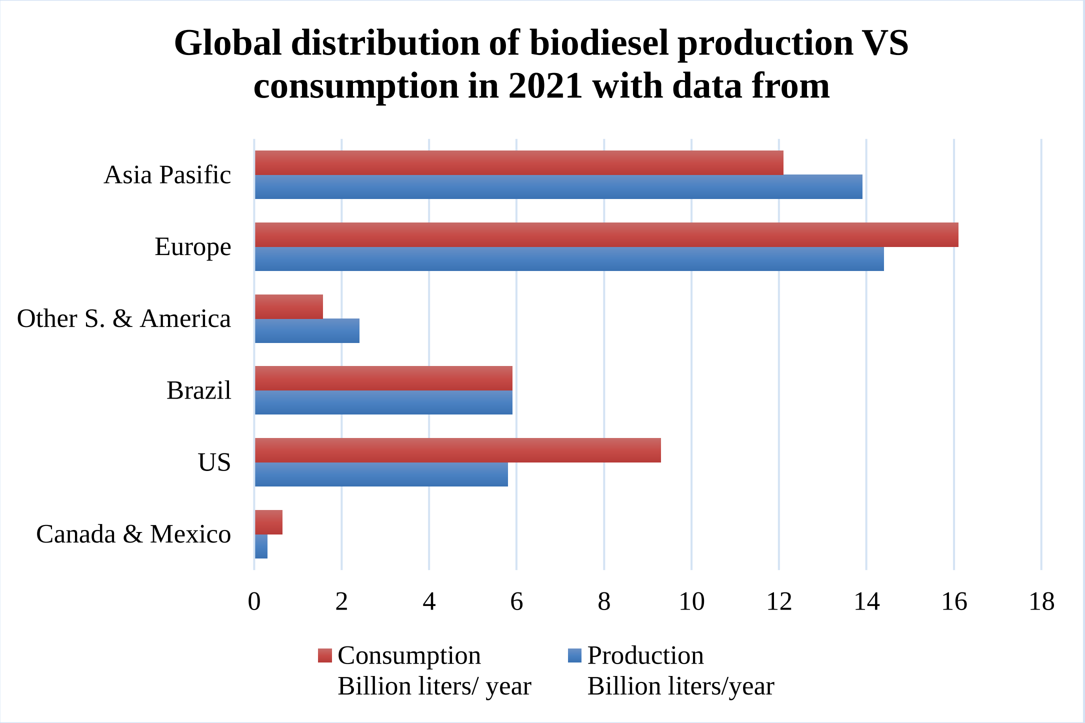

Fig. 3. Global distribution of biodiesel production VS consumption in 2021

Global biodiesel production has increased significantly in recent years, driven by the need to reduce carbon footprint and reliance on conventional diesel fuel [142]. Different countries use different feedstocks such as vegetable oils, inedible oils, algae oils, and WCO's for biodiesel production [143,144]. Advanced techniques such as transesterification of enzymatic and supercritical fluids have shown promise in increasing conversion rates and expanding feedstock options [145]. The world market for biodiesel is growing, with a focus on sustainability and carbon reduction through blending programs and regulatory mandates [146,147].

2.5 Financial Feasibility

This study evaluates the economic feasibility of biodiesel production from WCO using Life Cycle Cost Assessment (LCCA). LCCA refers to all costs associated with a product incurred during product production, and an economic model for product pricing [148,149]. When evaluating the economic feasibility of the WCO biodiesel production process, four processes are included, namely WCO collection, WCO pre-treatment, biodiesel production, and product delivery. Different resources have been involved, including labour, water, electricity, raw materials, equipment assets, etc., [150,151]. A breakdown of costs for WCO biodiesel production reveals that the WCO collection process accounts for a large portion of the total cost, with estimates starting at 15.60% to 83% [152]. These costs are influenced by factors such as the high purchase price of WCO raw materials and fluctuations in international oil prices [153,154]. In addition, the biodiesel production process contributes to the total cost, starting at 27.99% [155].

The cost of pre-treatment of WCO for biodiesel may vary depending on the method used. Studies show that pre-treatment using activated charcoal of avocado seeds can reduce free fatty acid (FFA) levels in WCO by up to 71.64% under optimal conditions at 10 g adsorption mass, 100 mesh particle size, 6 hours contact time, and 80°C temperature [156]. Fixed equipment costs accounted for 7.55%, and product shipments accounted for 3.44%. Commercial soybean oil, rapeseed oil, Jatropha oil, etc. are all refined oils that can be directly used in the transesterification process for biodiesel production, while WCO requires a pre-treatment process, so the cost of pre-treatment is classified into the cost of crude oil [157,158]. Therefore, the WCO cost is \$528.81 (WCO price and pre-treatment fee), accounting for 56.26% of the total cost [159]. The retail price of diesel is 49% crude oil cost, 14% refining, 20% taxes, and 18% distribution marketing [160]. So, the cost of diesel production accounts for 63% of the retail price, which is 568.74 USD/ton. Compared to the cost of diesel, the cost of WCO biodiesel is 65.28% higher [161]. Table 2 summarizes the prices of biodiesel products derived from different feedstock oils. Among the various oil feedstocks for biodiesel production, WCO is more cost-effective than other vegetable oils [162]. However, WCO recycling always faces challenges, for example, WCO is directly dumped down the sewer or illegally refined to produce vegetable oil again. The cost of WCO biodiesel is 939.98 USD/ton.

Table 2
The price of biodiesel from various raw materials

Feedstock oil	Price ($/ton)	Source
Palm oil	1,166.67	Jegannathan *et al.,* [163]
Castor Oil	1,904.76	Santana *et al.,* [164]
WCO	1,005.00	Zhang *et al.,* [165]
WCO	991.98	Sandhya *et al.,* [166]
Waste Oil	510.00	Marchetti *et al.,* [167]

In addition to oil raw materials, according to Liu *et al.,* [161] the WCO's biodiesel cost is influenced by the biodiesel production process, which is 27.99% of the total price. The selection of catalysts has a significant impact on the biodiesel production process. Some commonly used catalysts such as NaOH and CaO are commonly used [168]. CaO Heterogeneous catalysts, derived from eggshell waste or industrial sources, have shown promise as replacement catalysts, offering high transesterification activity and biodiesel yields. On the other hand, NaOH is a homogeneous type of catalyst common in biodiesel production, known for its effectiveness in the transesterification process [169]. The cost and process of catalyst preparation vary, affecting the overall economics of biodiesel production. For example, Aghel's *et al.,* [169] research examines the cost-effective use of WCO with CaO and MgO composites as catalysts [170]. Each type of catalyst requires certain optimal parameters, such as reaction time, temperature, and catalyst loading, to achieve maximum efficiency and meet international biodiesel standards [74]. The results showed that the cost of waste oil biodiesel was $ 0.51/kg [102]. It should be noted that NaOH catalysts have higher requirements for raw material oil, and the NaOH preparation process is more complicated [171]. Many studies have explored the utilization of CaO catalysts derived from various sources such as oyster shells, clamshells, lobsters, and eggshells for the transesterification of WCO into biodiesel [172,173]. According to the results of published research, CaO catalysts from oyster shells show more than 90% biodiesel yield in a short reaction time [173]. Another study examined that utilizing CaO catalysts in the transesterification process accounted for 18.17% of the total cost of biodiesel production [174].

The cost analysis indicates that collection and pre-treatment processes account for 56.26% of WCO biodiesel's total production cost, highlighting the need for optimization to improve economic feasibility. Although WCO biodiesel has higher initial costs compared to diesel, its environmental benefits and potential cost reductions through improved pre-treatment and catalysts like CaO—reducing transesterification costs by 18.17%—make it competitive. WCO biodiesel offers advantages in sustainability and waste management, crucial in the global energy market, and can contribute to a more sustainable energy mix as fossil fuel prices fluctuate [74].

3. Transesterification Process

Transesterification of WCO into biodiesel is an important process in sustainable energy production [175]. WCO is a viable raw material for biodiesel production, containing triglyceride levels and free fatty acids (FFA) [176,177]. To cope with high acidity WCO, a study explored esterification with glycerol to convert FFA into triglycerides before transesterification [178]. In addition, the CaO catalyzed glycerolises process significantly reduces the FFA content in biodiesel feedstocks to less than 3% under optimized conditions [179]. The transesterification leads to the optimization of parameters such as the methanol-to-oil ratio, catalyst concentration, and time for enhanced efficiency and meeting international standards [180]. The products of biodiesel produced from this reaction are fatty acid methyl esters (FAME) [181,182]. It usually occurs in the three-step pathways: triglycerides are converted to diglycerides; the diglycerides are converted to monoglycerides; the monoglycerides are transformed to glycerol and FAME [183-186].

3.1 Key Factors in Transesterification

In biodiesel manufacturing, the transesterification of fatty acids to alcohol, such as methanol, produces alkyl esters, which are in this case biodiesel. Required temperature conditions include 60–65°C a reaction time ranging from 1.5 to 3 hours and alcohol to oil in the ratio of 6:1 to 12:1 [187-191]. Such catalysts, ranging from homogeneous to heterogeneous catalysts, do the job with very high specificity and reactivity under very mild conditions quite well. Homogeneous catalysts such as alkaline catalysts have advantages and disadvantages, while heterogeneous catalysts such as clay-Na_2CO_3 show promise due to their superior activity and cost-effective biodiesel production potential. Table 3 below presents a comparison of the key factors affecting the transesterification process. These factors include temperature, time, type of catalyst, and alcohol-to-oil ratio.

Table 3
The comparison factors affecting the transesterification process

Key Factors	Comparison	Ref.
Temperature of the reaction	Generally, the reaction temperature ranging from 60-70°C is very essential in ensuring an optimum reaction rate. Increased temperature can lead to saponification, especially if there is an availability of free fatty acids in WCO.	Gao *et al.,* [192] Padder *et al.,* [193] Eze *et al.,* [194] Rizal *et al.,* [195]
Reaction Time	The ideal duration usually ranges from 1 to 4 hours. Inadequate response times can lead to reduced yields, whereas prolonged reactions do not substantially improve the quality of biodiesel	Khan *et al.,* [196] Dieng *et al.,* [197]
Classification of Catalysts	Catalysts can be categorized according to their phase: homogeneous catalysts (e.g., sodium hydroxide or potassium hydroxide) and heterogeneous catalysts (e.g., calcium oxide). The choice of a catalyst has a decisive influence on the reaction rate and the required purity of the product achieved.	Lani *et al.,* [198] Hsiao *et al.,* [199]
Alcohol-to-Oil Ratio	Reactions are developed generally using a high percentage of alcohol to promote a reaction effect. Ratios are usually from 6:1 to 12:1. The increase in the amount of alcohol increases the conversion efficiency but with a larger investment.	Kerras *et al.,* [200] Piloto-Rodríguez and Díaz-Domínguez [201]

3.2 Resources and Apparatus

Generally, double jacket reactors are used in the transesterification process of biodiesel production from WCO [175,202]. The heating system in biodiesel production helps in maintaining the requisite temperature for the transesterification process. Electrically driven separation technology (EDS) is a group of technologies that employ high voltage alternating current with high efficiency demonstrated during glycerol and contaminant removal from biodiesel, conforming to industry standards [183,184]. Different studies highlight the importance of temperature control for efficient reactions. The study by Stanescu *et al.,* [203] emphasizes the impact of temperature on reaction time and yield, showing an optimal temperature of 60°C for batch reactors [204]. In addition, Stanescu *et al.,* [203] compared the methods of electric heating (EH) and microwave-assisted heating (MW), noting that the MW process improves transesterification efficiency due to its ability to improve kinetics and reduce activation energy. Furthermore, Ghazidin *et al.,* [205] discussed the importance of heating control strategies in maintaining biodiesel quality, highlighting the effectiveness of derivative proportional control in achieving faster set point values without excess. Measuring instruments are used to accurately measure reactants and monitor the progress of the process. Biodiesel transesterification equipment from WCO and its functions can be seen in Table 4 as follows.

Table 4
The transesterification equipment process [206-210]

Apparatus	Utilization
Double jacket reactors	Typically, a stirred-tank reactor is used for batch processing
Separation units	Used to extract biodiesel from glycerol and excess alcohol
Heating systems	Used to sustain the necessary temperature for a chemical reaction
Measuring instruments	Used to accurately quantify reactants and oversee the progress of the process

3.3 Advancements in Biodiesel Production Technologies

Table 5 shows the analysis comparing parameters for biodiesel production. Supercritical fluid technology and enzymatic transesterification, which is a new technology, is becoming more and more popular [211-213]. WCO's environmental and economic impact analysis on biodiesel highlights its benefits in reducing waste and gas emissions [214,215]. For a better understanding, a detailed study of the biodiesel life cycle from WCO is needed, including its carbon footprint [216]. A holistic approach is needed to accurately assess the costs and benefits of WCO biodiesel, for sustainability [217,218].

Table 5
Analysis comparing parameters to produce biodiesel [219-222]

Parameter	Transesterification	Supercritical Fluid Technology	Enzymatic Transesterification
Temperature	60-70°C	Above a critical temperature of alcohol (e.g., 239°C for methanol)	30-50°C
Time	1-4 hours	8-12 minutes	Several hours to days
Catalyst	NaOH/KOH or CaO	Not required	Enzymes (e.g., lipases)
Alcohol-to-Oil Ratio	6:1 to 12:1	42:1 (for methanol)	3:1 to 6:1

4. Conclusion and Prospects for the Future

This study emphasizes the substantial environmental and economic advantages of manufacturing biodiesel from WCO. WCO-based biodiesel not only diminishes dependence on fossil fuels but also repurposes waste, so contributing to environmental preservation. The renewable and biodegradable characteristics of this product are in line with worldwide initiatives to address climate change and decrease carbon footprints. Consequently, it presents fewer environmental hazards when compared to conventional diesel fuel. Economically, WCO is a cost-effective raw material, ensuring a steady supply for biodiesel production. While the conversion from WCO to high-quality biodiesel presents challenges, particularly in pre-treatment processes, ongoing research is crucial for enhancing efficiency and cost-effectiveness. The findings demonstrate that WCO biodiesel performs well in engines, reducing emissions, especially in urban areas where air quality is paramount. WCO biodiesel's potential in urban transport is promising, and with further research, policy support, and public awareness, it could become a key player in global energy sustainability.

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