ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 7, Issue 1, 41-55

Unlocking the Power of Waste Cooking Oils for Sustainable Energy Production and Circular Economy: A Review

Samson Onoriode OKPO[1], Emozino Donatus EDAFIADHE[2]

[1]*Department of Chemical Engineering, Delta State University of Science and Technology, Ozoro*
okpos@dsust.edu.ng

[2]*Department of Mechanical Engineering, Delta State University of Science and Technology, Ozoro*
emozinode@dsust.edu.ng

Corresponding Author: *okpos@dsust.edu.ng,* +2348146763787

Date Submitted: *05/01/2024*
Date Accepted: *10/03/2024*
Date Published: *01/04/2024*

Abstract: *In the pursuit for sustainable energy solutions, biodiesel has come to prominence as an alternative to petroleum-derived diesel. This review delves into cutting-edge developments in production of biodiesel, emphasizing use of waste cooking oils (WCOs) as an environmentally friendly raw material. Incorporating waste cooking oils (WCOs) into the biodiesel production process not only tackles environmental issues associated with improper disposal but also adheres to the principles of a circular economy. This manuscript covers various methods and technologies for converting WCOs into high-quality biodiesel, emphasizing economic viability and environmental benefits. It discusses the potential of WCO-derived biodiesel to meet stringent fuel standards and reduce greenhouse gas emissions. Significant progress has been made in using waste cooking oils to generate sustainable energy, aligning with broader initiatives focused on renewable energy and circular economy principles. In summary, the utilization of waste cooking oils for biodiesel production presents an opportunity to shift away from reliance on fossil fuels, thereby fostering circular economy practices and sustainability goals.*

Keywords: *Biodiesel, Circular Economy, Green Technology, Renewable Fuels, Sustainable Energy, Waste Cooking Oils (WCO's).*

1. INTRODUCTION

The growing need for energy and the anticipated depletion of fossil fuel reserves have spurred research into renewable alternative fuels. By 2050, there will be a 50% increase in the world's energy demand [1]. There is a pressing requirement to shift towards renewable, low-carbon alternatives capable of replacing traditional energy sources. The worldwide quest for sustainable energy sources amid climate change and the diminishing availability of fossil fuels has prompted a fundamental shift in the way energy is produced and consumed.

As concerns about environmental impact grow, the need of transition to renewable and environmentally friendly energy sources becomes more urgent. One promising avenue within the renewable energy landscape is biodiesel. As defined by [2], biodiesel is formally identified as a "renewable fuel obtained through the transesterification process of triglycerides derived from edible oils, non-edible oils, and waste oils." Biodiesel is made up of monoalkyl esters derived from LCFAs (long- chain fatty acids) and has an elongated molecular structure with more than 12 carbon atoms in its carbon skeleton. This 100% pure biodiesel product is known as B100.

Biodiesel has been manufactured using diverse materials, including those from both plant and animal origins, whether edible or non-edible. According to [3], the first-generation biofuels were derived from edible sources, specifically oils obtained from crops such as canola, coconut, jatropha, maize, mustard, palm oil, peanut, rapeseed, soybean, sunflower, etc. Second-generation biofuels utilize non-edible sources for production [4], while third-generation biofuels employ innovative biomass production methods, notably utilizing algae as a primary feedstock [5-6]. So while second-generation biofuels aim to avoid using food as fuel, third-generation biofuels like algal biofuels bring new feedstock production methods to increase yields and lower costs. However, first- to third-generation, biodiesel feedstocks have disadvantages, including a vulnerability in the food supply that can increase the cost of food products, low yield, limited acreage, environmental adaptability, and high cost are barriers to producing biodiesel from some of the earlier feedstocks [7-8]. Ongoing research is dedicated to fourth-generation biofuels, aiming to offer more sustainable green energy solutions.

Research has raised worries about the potential conflict for essential resources like water, energy, and land for food and fuel production, as highlighted in studies by [9]. This highlights the need to find inexpensive, non-food feedstocks for biodiesel production. As a result, researchers have explored making biodiesel from alternative, non-food sources [10-11].

Waste cooking oils are increasingly recognized as a promising feedstock option with transformative potential and environmental responsibility. They offer a solution that sidesteps competition with food resources while simultaneously bridging the gap between waste management and sustainable energy generation. Researchers have employed various terms to refer to edible cooking oil in different studies. [12-13] have used the term "waste cooking oil" (WCO). Alternatively, [14] have denoted it as "used cooking oil" (UCO), while [15] have utilized the term "used frying oil" (UFO).

This manuscript presents a comprehensive review of the paradigm shift enabled by waste cooking oils, highlighting their role in promoting sustainable energy generation and contributing to the principles of circular economy. By exploring the technical advancements, economic viability, environmental benefits, and real-world case studies, this manuscript offers a holistic understanding of how waste cooking oils can transform the biodiesel landscape.

2. WASTE COOKING OILS: AN ABUNDANT RESOURCE

Numerous investigators, such as [15, 16, 17, 18, 19] have explored the viability of using WCO as a promising source for the production of biodiesel. Nevertheless, these investigations have not adequately considered the sustainability aspect associated with the utilization of waste cooking oil (WCO) in biodiesel production. WCO exhibits potential as a valuable resource within the framework of the circular economy. Math et al. [20] have reported that substantial quantities of WCO can be found worldwide. Nevertheless, the collection of this waste poses a notable challenge, with substantial amounts of used cooking oil being illicitly disposed of in landfills and rivers, contributing to environmental pollution [20-21]. According to [22], global vegetable oil production was 208.8 million metric tonnes in 2021/2022 and is expected to exceed 217 million metric tonnes in 2022/2023. This surge in production is attributed to growing demands driven by global population growth, leading to a proportional increase in waste cooking oil. Because different countries have different culinary traditions, the amount of WCO produced varies significantly across them [23].

Worldwide, the annual production of Waste Cooking Oils (WCOs) from both residential and commercial sources is projected to surpass 15 million metric tons. Research conducted by [24] indicates that the European Union (EU) contributes roughly one million tons per year, which is noteworthy in this context. Furthermore, as indicated by the study referenced in [20] and [21], Table 1 presents the annual generation of waste cooking oil (WCO) in specific selected countries.

Table 1: Annual waste cooking oil (WCO) generation in some selected nations [21]

Country	**Quantity (million tons/year)**
Canada	0.12
China	4.5
Europe	0.7-10
Ireland	0.153
Japan	0.45-0.57
Malaysia	0.5
Taiwan	0.07
UK	0.2
USA	10

In Africa, with a specific focus on Nigeria, the continent's most populous country, WCO stands out as one of the substantial wastes produced in hotels, restaurants, and pubs. Disposing of this waste poses a significant challenge [25]. Regrettably, unlike developed nations, Nigeria lacks an information management authority that systematically records the generation of WCO, as noted by [15]. In addition to inadvertent social practices and the absence of comprehensive regulations for proper used oil disposal in numerous countries, the recovery of waste materials, particularly used cooking oil (WCO), remains suboptimal [26].

Africa has abundant sources of WCO that can be converted to biodiesel to meet increasing energy needs. Studies at universities in Africa, particularly in Nigeria, have shown that efficient methods for producing high-quality biodiesel can be produced from waste oils from hotels, cafeterias and households [27-28]. African researchers are at the forefront of exploring the use of WCO as a viable feedstock for biodiesel production, driven by continent's growing interest in sustainable energy solutions and environmental protection. Studies such as those by [29-32] have investigated various aspects of WCO-based biodiesel production, including the characterization of raw materials and production techniques. Amenaghawon et al. [30] have conducted optimization studies on the use of WCO for the biodiesel production process to maximize efficiency and minimize environmental impact. For example, researchers have investigated various catalysts and reaction conditions to improve transesterification of WCO into biodiesel while ensuring cost efficiency and sustainability. Various studies conducted by African researchers have demonstrated biodiesel yields of over 80% by optimizing key transesterification reaction parameters such as temperature, methanol ratio and reaction time [29-30]. Environmentally friendly and economically viable biodiesel low-cost feedstock like WCO can be crucial to Africa's energy sustainability.

However, further research initiatives and knowledge exchange are needed between African researchers and international partners who have played a crucial role in advancing research in this area. By promoting interdisciplinary collaboration and the integration of Stakeholders African researchers continue to contribute to the development of sustainable energy solutions that address both environmental concerns and socio-economic development needs across the continent.

2.1 Waste Cooking Oil Sourcing and Collection Strategies

Efficiently collecting waste cooking oils from widespread generators remains an operational and economic challenge [33]. Multi-tiered collection networks and bulk transport optimization can help consolidate waste volumes. The majority of waste cooking oil (WCO) is sourced from residential kitchens [26; 34; 35]. The unregulated disposal of waste cooking oil leads to adverse environmental effects and economic losses. Improperly disposing of waste cooking oil has negative impacts on the environment and can result in financial losses. Conversely, properly collecting and managing waste cooking oil is beneficial not only for the environment but also economically attractive [36]. [33; 37] have categorized sources of waste cooking oil into two sources namely commercial (hotels, restaurants, canteens, food processing industries, catering etc.) and households. Unfortunately, just a small per cent of the total WCO generated is recovered indicating significant room for improved collection systems. According to [23], setting up public collection points in places that are easily accessible (such as schools, supermarkets, parking lots, government buildings, recreational facilities, etc.) is by far the most popular collection option. Collecting and recycling waste cooking oil (WCO) helps address three environmental challenges: decreasing waste through product reuse/recovery, lessening dependence on fossil fuel energy, and mitigating emissions of pollutants, as mentioned in [33].

Therefore, dedicated oil storage tanks or containers in conjunction with routine private used oil collectors are crucial for the collection of used cooking oil. In addition, several countries have enacted regulations and mandated residents to safely dispose of commercial WCO to authorized collectors rather than to sewers [35]. Furthermore, researchers have proposed implementing policies to regulate the recycling, transportation, collection, and reuse of WCO. This could assist in reducing environmental problems and dangers stemming from inadequate management of waste cooking oil [38].Overall, a distributed collection infrastructure with community participation, business incentives, and effective storage and transportation coordination is required to take advantage of the diffuse global availability of WCO.

There remains a significant gap in the academic literature regarding effective planning and infrastructure development for collecting used cooking oil waste. Previous studies by [39] have noted insufficient research in this area has given rise to several theoretical issues and practical hurdles in implementing waste cooking oil collection programs. Furthermore, analysis by [40] suggests existing collection schemes fail to fully realize the societal and sustainability gains offered by repurposing domestically sourced waste oils. Addressing this knowledge shortage through new studies could provide models to maximize the environmental and social benefits of reusing this form of post-consumer waste. A systematic infrastructure planning methodology is critically needed to unlock potential of localized WCO recycling initiatives.

2.2 Pretreatment Requirements and Methods

In contrast to pure vegetable oils, WCO contains increased amounts of free fatty acids (FFA), moisture, solid particles, glycerides, polymers, oxidized compounds and other contaminants [41]. This is due to thermolytic, oxidative and hydrolytic degradation of the triglyceride structure during cooking at high temperatures in the presence of air and water [21]. High FFA content results in soap and water formation during the conventional base-catalyzed transesterification process [42]. This creates emulsions and increases separation costs. Water causes hydrolysis competing with transesterification. Particulates can clog reactors and poison catalysts. The presence of diglycerides, monoglycerides and oxidized lipids also lowers biodiesel yields. Collected oils undergo a series of pre-treatment steps before conversion to biodiesel. Chemical and physical methods are used to remove contaminants including high FFAs, water, and solid food particles. The integration of different pre-treatment technologies allows for the optimization of feedstock purity, stability, and quality. Table 2 displays various characteristics of waste cooking oils (WCOs) as documented by different researchers. As indicated in Table 2, the attributes of WCO's documented in the three studies exhibited some variability, likely stemming from differences in the source of oil, cooking techniques employed, and conditions of storage prior to analysis. However, the overall property values were largely comparable and were within an acceptable range for WCO's. Substantial variances were observed in the level of unsaturation, oxidation, free fatty acids, and viscosity, indicating disparities in the degradation of the oils. But overall, the oils had the expected properties that could be considered as raw materials for renewable fuels or other uses to recycle used cooking oils. Despite their origin from different regions and different methods, the studies confirm that used cooking oils are valuable potential resources with characteristic properties that make them suitable for further processing and use.

2.2.1. Methods for pre-treatment of waste cooking oil (WCO)

EUBIA [21] discovered that pre-treatment techniques for WCO involve physical processes to eliminate suspended solid impurities and chemical methods primarily for deacidification. WCO's can contain approximately 10-20% solids by volume [21, 45]. The first phase of treatment of WCOs involves removal of particles and suspended solids, including food residues (such as skin, bones, leftover food, etc.), paper, cardboard, plastics, carbonized materials and aggregates [38]. According to [46], the pretreatment strategies aimed at eliminating particulates and suspended solids from used cooking oil before its conversion into biodiesel encompass various methods such as filtration, gravity sedimentation, absorption treatment, and centrifugation.

Table 2: Waste cooking oil (WCO) properties reported by various researchers

Properties	**[18]**	**[43]**	**[44]**
Density (g/mL)	0.93	0.927 ± 0.02	0.80 ± 0.06
Acid value (mg KOH/g)	5.78 ± 0.11	1.4 ± 0.06	9.41±0.19
Saponification value	172.65 ± 0.31	180.6 ± 0.45	208.18 ±0.40
Iodine value	95.85 ± 0.55	103 ± 0.55	76.14 ±0.34
Peroxide value			11.30 ±0.34
Sediments	1.17 ± 0.01		
Humidity	1.34 ± 0.03		
Dynamic Viscosity	4.49 ± 0.02		
Kinematic viscosity		45.5 ± 0.5	
Water content (wt %)		0.0252 ± 0.003	0.90 ±1.02
Refractive index			1.45 ± 0.12
Free fatty acid-FFA (wt %)		0.7 ± 0.08	5.27 ±0.75
HHV (kJ/kg)		40 480	

i. Filtration/settlement

As outlined by [46], the initial stage involves subjecting waste cooking oil (WCO) to heat and subsequent filtration through sieves. During the settling phase in a designated tank, impurities such as dirt and water segregate and accumulate at the bottom. The utilization of heat serves a dual purpose, both reducing moistness and preserving inherent quality of the oil [47].

ii. Centrifugation

This approach effectively tackles solid impurities and reduces water content in the oil, as indicated by [38]. It is a prevalent method in the large-scale production of biodiesel from vegetable oils, as noted by [48]. Nevertheless, it is essential to acknowledge that capital and operating costs associated with this process are relatively high.

2.2.2. Waste cooking oil FFA reduction methods

Free fatty acid pretreatment options commercially available include esterification; adsorption; neutralization; distillation/deodorization; and glycerolysis [38, 46].

i. Esterification

In this method, used cooking oil is combined with enzymes, specifically lipases, or an acid catalyst [38]. The aim is to convert free fatty acids (FFA) and other acidic compounds into esters. Nevertheless, this method is accompanied by several limitations, including challenges related to catalyst recovery, susceptibility of equipment to catalyst corrosion, and relatively elevated processing costs, as articulated by [46].

ii. Adsorption

Waste cooking oil is treated with a specific material to selectively remove constituents such as polar molecules [38, 49], efficiently removes free fatty acids (FFA), moisture, and other polar chemicals, including peroxides [50]. During the adsorption process, various commonly utilized adsorbents are employed, including activated carbon, aluminium hydroxide, aluminium silicates, clays, ion exchange resins, magnesium oxide, silica gel, zeolite, among others. This approach is known for its cost-effectiveness.

iii. Neutralization

The chemical neutralization method involves the blending of WCO with alkaline solutions such as NaOH or KOH. This chemical reaction converts FFA to solid soap, which, being insoluble in the oil, is removed through series of washing steps involving water spray, and followed by decantation or centrifugation. As elucidated in the studies conducted by [38, 46, 50], this method effectively reduces the levels of FFA's in WCO.

iv. Distillation/deodorization

As [46] point out, vacuum and stripping distillation are extensively used in vegetable oil sector to remove FFA. This method is also effective in clearing other contaminants, as indicated in the work of [50]. In industrial settings, distillation is frequently paired with adsorption to handle removal of polar complexes [50]. However, as stated in [46], the need for vacuum equipment, high energy consumption, and rising temperatures make distillation more expensive to set up and run than other pretreatment techniques. Therefore, the distillation process is considered more complex and costly than other pretreatment processes.

v. Glycerolysis

The process involves combining glycerol, a by-product from biodiesel production, with WCO having a substantial free FFA concentration, typically exceeding 5% [46]. At elevated temperatures, glycerol undergoes a reaction with FFA resulting in formation of glycerides. This process offers distinct advantages, including the ready availability of glycerol, the exclusion of alcohol (unlike esterification methods), and the immediate vaporization of water generated during the reaction [51]. However, it's essential to note that this method requires high temperatures and exhibits a relatively slow reaction rate [46].

vi. Other FFA reduction techniques

Cardenas *et al*. [38] have listed supercritical fluid extraction, biological treatment, membrane separation, solvent extraction among others as alternative techniques for reducing/removing FFA from WCO.

3. BIODIESEL CONVERSION PROCESSES

Traditional techniques for deriving biodiesel from oils and fats encompass utilizing the oil directly, creating microemulsions, employing pyrolysis, and conducting transesterification reactions [52]. Extensive research indicates that transesterification is widely acknowledged as the most practical and commonly employed technique for deriving biodiesel from oil/fat feedstocks [52-53]. Consequently, transesterification has become the predominant method in commercial applications for transforming vegetable oils into environmentally sustainable and clean fuel, exemplified by biodiesel [52]. After the pre-treatment phase, the biodiesel production process utilizing WCO adheres to established conventional methods employed in the processing of native vegetable oils, as elucidated in the research done by [54].

In the conventional biodiesel synthesis process, a pivotal step is the transesterification of vegetable oil. This fundamental procedure involves the conversion of triglycerides present in fats and oils into biodiesel and glycerol. The efficiency of this reaction is influenced by presence or absence of a catalyst, a topic extensively discussed by [21]. Specifically pertaining to WCO, the transesterification process occurs when the oil reacts with alcohol, predominantly methanol, in the presence of a catalyst. This reaction yields biodiesel (FAME) and by-products such as glycerin. Methanol is favoured due to its rapid reactivity with triglycerides and its compatibility with a catalyst, expediting the process [46]. Utilizing a catalyst accelerates the transesterification process, whereas non-catalytic methods necessitate elevated temperatures and pressures [46]. To foster a comprehensive understanding of the properties inherent in waste cooking oil (WCO) biodiesel, a series of analyses have been meticulously conducted by researchers. The outcomes of these analyses are meticulously delineated in Table 3, where the acquired results are systematically compared against the established standards. This comparative assessment serves to elucidate the distinct characteristics of WCO biodiesel as investigated by various scholars in the field.

A comparison of reported biodiesel property values with established standards in Table 4 shows good agreement on several critical parameters, while others show some degree of variability. In particular, the reported values for specific gravity, kinematic viscosity and cetane number are within the specified ranges indicating compliance with the specifications of these standards. In particular, the reported flashpoints of 135 °C and 150 °C exceed the minimum thresholds specified in [2] and [58], thereby meeting safety requirements. In terms of cold flow property, the biodiesel variants derived from WCO exhibit satisfactory cloud and pour points that meet [2] standards. However, [58] did not specify any explicit limit values in this regard.

The acid values, which range between 0.14 and 0.5, closely correspond to the <0.5 mg KOH/g limits set by [2] and [58] standards, indicating a low FFA. Furthermore, with a sulfur content of 0.0094%, well below [2] limit of 0.05%, the biodiesel has the characteristics of an ultra-low sulfur fuel. Although no specific pH standards have been defined, the recorded value of 7.43 suggests that the WCO biodiesel is neutral. Importantly, [43] determined a distillation temperature of 345 °C, a value very close to the 360 °C specified in [2]. This agreement underlines the general agreement of the reported biodiesel variants with key indicators such as density, cetane number, flash point and acid number confirms their compliance with the strict specifications and quality standards set out in both [2] and [58].

3.1 Conventional Transesterification Limitations

Conventional transesterification is a prevalent method of manufacturing biodiesel. It requires processing triglycerides with an alcohol in the presence of a catalyst to make glycerin and biodiesel. This approach is commonly employed, but it faces some obstacles and restrictions that prevent it from reaching its full potential. These include but are not limited to, raw material limitations, process inefficiencies, catalyst costs, energy intensity, separation difficulties, soap formation and methanol recovery. The operational efficiency of conventional transesterification is intricately influenced by the specific nature and concentration of the catalyst utilized, as expounded upon in the studies of [59-60]. Catalytic transesterification reactions are conducted through the application of either chemical or enzymatic catalysts. Chemical catalysts are classified as either homogeneous or heterogeneous [60]. As shown in Table 4, research has documented the benefits and drawbacks of several types of catalysts used in the manufacture of biodiesel.

Table 3: WCO biodiesel Properties

Properties	**[46]**	**[54]**	**[55]**	**[56]**	**[57]**	
					[2] ASTM D6751	**[58] EN 14214**
Specific Density @15 °C	0.88	0.887	0.870		0.88	0.86 - 0.90
Kinematic viscosity @ 40 °C (mm^2/s)	4.2	4.2	4.8	5.2	1.9 – 6	3.5 -5.0
Cetane number(CN)	47.6	47.7 -59.8	49.84		47 Min	
pH						
Diesel index(DI)			55.33			
Flashpoint (FP) (°C)	135	150	180	96	130 Min	101 Min
Pour point(PP) (°C)	-3	7	-1		-15 to -16	-
Cloud point (CP) (°C)	-3	10	-	9	-3 to -12	-
Aniline point (AP) (°C)			87.5			
API gravity			29.2			
Heat combustion (cal/g)						
Distillation temperature (°C)	345				360	-
Lower Calorific Value		39.26 – 40.57				
Acid value(AV) (mg KOH/g)	0.14		0.45	0.497	0.5 Max	0.5 Max
Free Fatty Acid(FFA)		0.76				
Iodine value(IV) (mg I_2/100g)	113	83			-	-
Saponification value(SV)		207			370 max.	
Water and sediment	0	0.8 – 1.9	0.01	0.02	0.005 vol. %	500 mg/kg
Sulphur content (%)	0.00			0.0143	Max 0.05	

3.2 Transformative Biodiesel Conversion Technologies

Despite its inherent drawbacks, conventional biodiesel transesterification is an essential step in creating a sustainable fuel. Due to all the issues with traditional biodiesel transesterification, new alternative production techniques are always being discovered. These techniques include enzymatic transesterification, ionic liquids as catalysts, microbial conversion, microwave method, plasma-assisted conversion, supercritical transesterification method, and ultrasonic-assisted method [63]. These cutting-edge conversion technologies point the path toward a future where biodiesel production is more environmentally friendly.

3.2.1 Catalytic distillation

Catalytic distillation is an emerging environmentally friendly reactor technology that combines chemical reactions and product separation in a single step [64-65]. This approach allows simultaneous execution of reactions and separation, contributing to higher product yield and overall productivity [66]. Catalytic distillation offers advantages like mitigating catalyst hotspots, improving temperature control, and enhancing energy integration. Recent research touts it as a breakthrough in efficient and cost-effective biodiesel production [65]. Neupane [64] notes a drawback, emphasizing the dependence of the conversion process and solvent use on catalyst recovery.

3.2.2 Enzymatic transesterification

Enzymatic transesterification, using lipases as catalysts, shows promise for converting WCO into biodiesel, offering an eco-friendly alternative to fossil fuels [67]. This process operates under mild conditions, with low energy consumption and the potential use of lower-quality feedstocks like WCO [68]. Despite challenges such as enzyme cost and potential deactivation, enzymatic transesterification is considered more environmentally friendly and sustainable than traditional chemical methods [69].

3.2.3 Hydrodynamic Cavitation

According to [70], hydrodynamic cavitation stands out as an energy-efficient method for alkyl ester (biodiesel) synthesis. The process involves creating cavities by reducing pressure as liquid flows through constriction, generating cavitation bubbles that break down triglycerides into biodiesel and glycerol. In the words of [70], key operational variables influencing conversion and yield include oil-to-alcohol molar ratio, kinetics, cavitation number, inlet pressure, reaction temperature, and system geometry. These variables are crucial in determining the efficiency of the hydrodynamic cavitation process for biodiesel synthesis. According to study conducted by [71], the hydrodynamic cavitation technique for biodiesel was characterized as a straightforward, efficient, time-saving and environmentally friendly thereby affirming its practical feasibility in industrial applications.

Table 4: The advantages and disadvantages of various types of catalysts used in biodiesel production.

Catalysts type	Examples	Advantages	Disadvantages	References
Homogeneous	NaOH, KOH, H_2SO_4, HCl	High catalytic activity, affordable, good kinetics, and mild. Preferred method for low-quality raw materials	The FFA requirement is low, the conditions are anhydrous, saponification takes place, emulsion is formed, more wastewater is generated during purification, and everything is disposable. Unlike heterogeneous catalysts, hazardous to environment. Hygroscopic nature (NaOH, KOH) Equipment deterioration, increased neutralization waste, challenges with recycling, extended reaction times, elevated reaction temperatures, and low catalytic activity.	[61-62]
Heterogeneous.	Cao, MgO, CaTio, WO_3/ZrO_2,$SiO_2/Zr0_2$	Environmentally friendly, recyclable, less problematic to dispose of, easily separated, more selective, and having a longer catalyst lifetime. Enable both transesterification and esterification at the same time to prevent the production of soap.	Lower FFA requirement, anhydrous conditions, higher wastewater treatment, high reaction temperature and pressure, diffusion limitations, high cost and high alcohol to oil molar ratio required. Diffusion limitations, low microporosity, low acid centre concentrations and high cost.	[61-62]
Biocatalyst or enzyme catalyst	Lipozyme, lipozyme TLIM, novozym 435, lipozyme RMIM	Prevent the production of soap, non-polluting, and make the purification and catalyst-product separation process simpler. Recognize that free fatty acids and water are present. i.e. High likelihood of catalyst regeneration and reuse.	Exceedingly costly and potentially cause the enzyme to become denatured. a very slow reaction rate resulting in a long processing time.	[61-62]

3.2.4 Ionic liquids as catalysts

The process involves catalysis using ionic liquid-supported acids/bases or enzymes [72]. Ionic liquids, modern materials with organic salts or eutectic blends of anions and cations, remain in a liquid state below 100 °C [73]. They offer both homogeneous and heterogeneous catalytic properties, making them potential alternatives to traditional catalysts in biodiesel synthesis [74]. Ionic liquids have unique features, such as solubility, non-volatility, and environmental friendliness, positioning them as substitutes for alkali catalysts [75]. Challenges like cost and recovery processes limit their broader use in biodiesel production [75-76]. Categorized by cations, popular types include quaternary ammonium and 1-alkyl-3-methylimidazolium ionic [77]. Moreover, [78] have stated that specific ionic liquids, such as 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, are gaining popularity as environmentally friendly solvents in biodiesel production. These ionic liquids exhibit versatility in various applications for biodiesel synthesis across diverse feedstocks.

3.2.5 Microbial conversion

Microbial biodiesel production utilizes oleaginous microorganisms like bacteria, yeast, and fungi to convert organic materials into biodiesel through metabolic pathways, offering a sustainable approach [79]. The process involves the microbial conversion of renewable materials into microbial oil, further used in biodiesel production via transesterification [79]. Two primary methods, direct and indirect microbial conversion, are employed based on the microorganism and starting material [80]. Despite challenges, such as low conversion yields and technical complexities, microbial biodiesel production holds promise due to its flexibility, emission reduction potential, and cost-saving opportunities [79]. Ongoing research aims to enhance microbial biodiesel production's potential.

3.2.6 Microwave-assisted transesterification

The utilization of microwaves for heating and catalyzing reactions has emerged as promising and innovative methodology, offering substantial advantages over conventional approaches [81-82]. This technique proves to be advantageous as it accelerates the reaction kinetics and minimizes energy consumption as it can utilize the thermal conductivity within the reaction mixture [83]. Microwave-induced heating enhances heat transfer efficiency, resulting in significantly reduced reaction durations, especially beneficial in the context of microwave-assisted transesterification for biodiesel synthesis.

The microwave heating methodology is distinguished as an environmentally friendly and sustainable technology with versatile applications, spanning waste treatment, soil remediation, sediment management, and water purification, owing to its inherent rapidity and energy efficiency [84]. However, the realization of these advantages is not without challenges, as considerations of equipment, safety protocols, catalyst selection, and downstream processing require meticulous attention. A notable drawback is the substantial cost associated with the microwave method, primarily attributable to the significant capital investments required for acquiring and maintaining the requisite equipment [85].

3.2.7 Plasma-assisted conversion

Plasma-assisted conversion, a novel technology in biodiesel production, utilizes ionized gas generated under specific conditions, offering advantages over conventional methods. These include milder reaction conditions, faster reaction times, versatility in feedstock, and catalyst usability without deactivation, even in presence of impurities [52, 86]. Plasma reduces viscosity, enhancing oil, alcohol, and catalyst mixing in transesterification at low temperatures, achieving high biodiesel conversion yield of around 98% [87]. Despite its promise, challenges such as optimizing plasma parameters and scaling need addressing before widespread adoption. Ongoing research and development indicate the significant potential of plasma-assisted conversion in revolutionizing biodiesel production for a more sustainable biofuel industry.

3.2.8 Supercritical fluid transesterification

In comparison to traditional catalyst transesterification, research by [63; 88] reveals that supercritical transesterification offers faster and more environmentally friendly biodiesel production with higher conversion rates. This method eliminates the need for catalyst preparation and separation, using supercritical fluids like carbon dioxide (CO_2) instead of methanol. Additionally, it allows the simultaneous conversion of free fatty acids (FFA) and triglycerides, accommodating various feedstocks with minor deviations from quality standards [89]. Despite its advantages, supercritical transesterification has drawbacks such as high molar ratios, temperatures, and pressures, which increase expenses [70, 90]. Despite concerns, supercritical transesterification remains a high-conversion, fast, and environmentally friendly production process [63].

3.2.9 Ultrasound-assisted technique

Ultrasound-assisted biodiesel production employs high-frequency ultrasound waves to enhance the transesterification reaction, typically operating at frequencies between 20 and 50 kHz with power exceeding 200 W [52, 91]. This technique induces cavitation bubbles, leading to localized high temperatures and pressures that accelerate the reaction. Advantages of ultrasound-assisted biodiesel production include increased reaction speed, higher biodiesel yield, and lower energy consumption, reduced catalyst requirements, and simplified product separation. Recent research by [92] demonstrated biodiesel production from soybean oil using both high-frequency ultrasonography (1 to 3 MHz) and low-power ultrasonography (6 to 9 W).

4. CIRCULAR ECONOMY INTEGRATION AND SUSTAINABILITY

In a study carried out by Geissdoerfer et al.[93], circular economy is described as a regenerative system with the goal to reduce resource consumption, waste, emissions, and energy losses. This is accomplished by intentionally slowing down, closing, and narrowing material and energy cycles. Figure 1 illustrates the circular economy model for WCO, emphasizing efficient resource management, recycling, and sustainability to minimize waste and maximize resource utilization. This approach reduces waste, pollution, and carbon emissions.

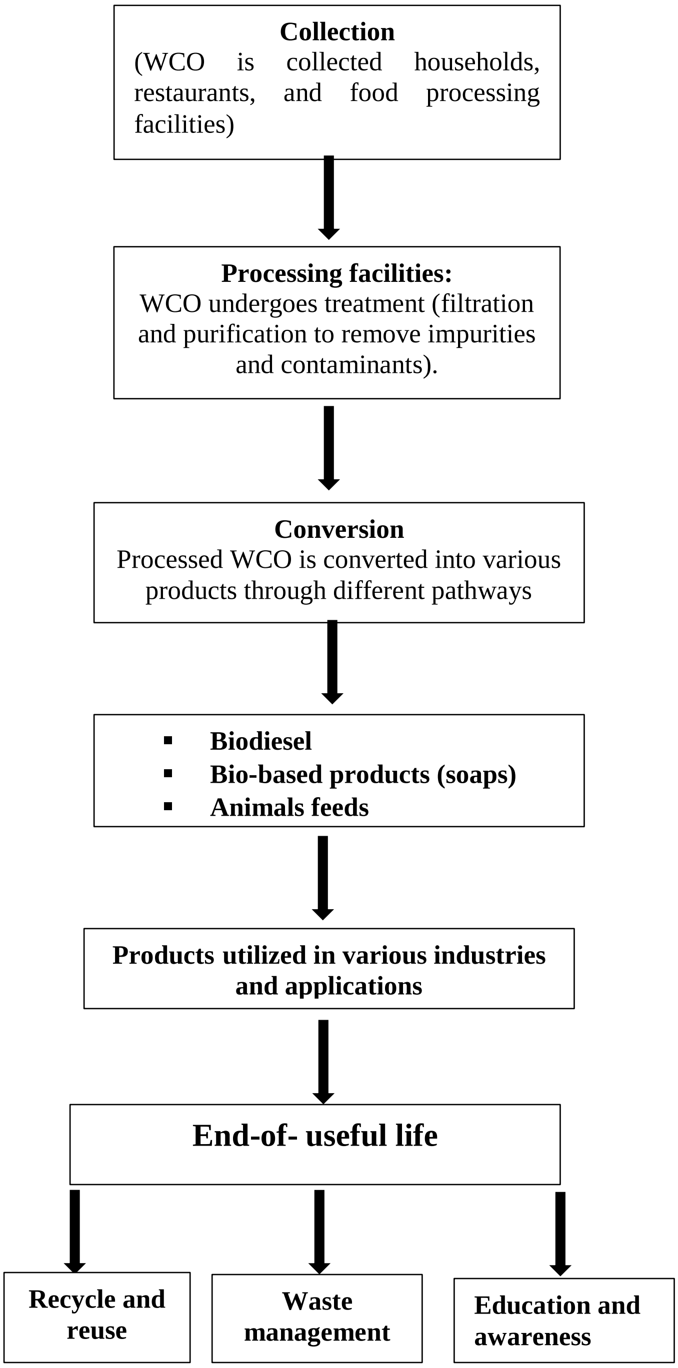

Figure 1: Schematic block diagram of circular economy of waste cooking oil (WCO)

A great opportunity lies in the use of WCO as a renewable raw material. Globally, yearly production of WCO from residential and commercial sources is expected to surpass 15 million metric tons. In this context, the European Union (EU) contributes around one million tons annually [94]. Developing efficient WCO collection systems helps provide a consistent feedstock source. Policies mandating WCO collections and recycling from large generators like residential homes, restaurants, hotels and institutional food services companies have been enacted in South Korea and Taiwan [34, 95].

Several factors contribute to the resurgence of interest in WCO's as a biodiesel feedstock. Their abundance resulting from widespread use makes them a readily available and renewable resource. Furthermore, the economics of biodiesel production from waste cooking oils are improved due to the comparatively lower costs compared to native vegetable oils. Used cooking oils, often discarded after culinary use, have traditionally posed a challenge to waste management as they can clog drainage systems and contribute to environmental pollution. However, these oils are increasingly recognized for their untapped potential within a circular economy framework. Sadly, the considerable amount of improperly disposed cooking oil poses threats to both human and animal health when consumed. Furthermore, if not managed adequately, it can also have detrimental effects on the environment [12, 96]. The by-products that emerge predominantly through the oxidation mechanisms of the WCO have been characterized for their carcinogenic attributes [97]. An oil layer on water surfaces reduces oxygen absorption, leading to marine life decline. The oil-water mixture raises chemical oxygen demand (COD), making water toxic from oil degradation by-products. Carcinogens taken up by marine organisms enter the human food chain, posing health hazards [84, 98].

The use of used cooking oil (WCO) in biodiesel production contributes significantly to the Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action). By repurposing WCO into biodiesel, renewable energy sources are promoted [99], aligning with Goal 7. This practice also embodies sustainable consumption and production patterns by transforming waste into a valuable resource, in line with Goal 12 [99]. Moreover, WCO biodiesel reduces carbon emissions, thus aiding in climate change mitigation efforts, which resonates with Goal 13 [99]. Therefore, use of WCO in biodiesel production contributes significantly to advancing these SDGs, promoting renewable energy, responsible consumption, and climate action [99].

Converting waste oils into biodiesel minimizes their environmental impact. Rather than discharging used cooking oils into waterways and sewers where they cause pollution, these oils can be collected and recycled into sustainable biodiesel production. This provides an alternative way to utilize waste cooking oils while avoiding harmful clogging of drainage systems and damage to aquatic ecosystems. Diverting WCOs into biodiesel provides waste management and renewable energy benefits. WCO biodiesel can also compete economically with petro-diesel at scale. WCO holds promise as a valuable resource in the circular economy. Through proper collection and management, conversion to biofuels, and utilization in diverse industrial applications, WCO contributes to resource efficiency and waste reduction. Addressing challenges and promoting research in this area can lead to a more sustainable and circular approach to WCO management.

5. ECONOMIC VIABILITY AND MARKET DYNAMICS

As [100] highlights, the economic dynamics of biodiesel production is significantly influenced by raw material costs. It is crucial to explore low-cost raw material options including WCO, animal fats and inedible oil crops. According to [101], biodiesel derived from vegetable oil faces higher production costs, prompting increased interest in exploring more cost-effective feedstocks. WCO emerges a viable option for biodiesel synthesis. Thorough techno-economic studies carried out by researchers, utilizing lipase, acid, and base as catalysts, revealed a significant decrease in the cost of biodiesel production when acid and base catalysts were employed. Acid catalysts were identified as the most economically favorable, while lipase catalysts were considered the costliest [101]. The alkaline-catalyzed transesterification process is recognized as the most economically efficient method for large-scale production of biodiesel [100,102].

Economic viability factors for biodiesel production facilities include feedstock costs, equipment expenses, and biodiesel selling price, glycerin revenue, and production capacity [100]. The economic analysis conducted by [103] and [104] on the use of WCO for biodiesel production are summarized in Table 5 and Table 6, respectively.

Tables 5: Economic analysis of biodiesel production using WCO

Cost and revenue components	Cost
Total Capital investment	Rs. 1,615,133,000
Operating cost	Rs. 2,075,333,000/year
Main revenue	Rs. 2,261,222,000/year
Other revenues	Rs. 104,373,027/year
Total revenues	Rs. 2,365,586,000/year
Cost basis annual rate	40,499,171 kg/year
Unit production cost	Rs. 51.24/kg
Net unit production cost	Rs. 51.24/kg
Unit production revenue	Rs. 58.41/kg

As presented in Table 4, the capital investment of Rs 1.6 billion establishes a biodiesel facility with 40.5 million kg per year capacity utilizing waste cooking oil feedstock. Annual operating expenses are projected at Rs 2.1 billion, while revenues from 40.5 million kg biodiesel sales and by-products amount to Rs 2.4 billion. The unit production cost is Rs 51.24 per kilogram of biodiesel, matching the net cost without subsidies. Against this, the unit revenue from biodiesel sales is Rs 58.41 per kg, enabling profitable operations.

Table 6: Economic analysis of biodiesel production using WCO

Cost and return components	**Cost**
Gross production value ($\$L^{-1}$)	2.499
Variable production cost ($\$L^{-1}$)	1.197
Fixed production cost ($\$L^{-1}$)	0.004
Total production cost ($\$L^{-1}$)	1.201
Total production cost ($\$Kg^{-1}$)	1.057
Gross return($\$L^{-1}$)	1.302
Net return ($\$L^{-1}$)	1.298
Benefit to cost ratio	2.081
Productivity ($\$Kg^{-1}$)	0.946

The data presented in Table 5 indicate that biodiesel production from waste cooking oil is a profitable process with attractive margins. Specifically, with a gross production value of $2.499 per litre, total production costs of $1.201 per litre, gross and net returns of $1.302 and $1.298 per litre respectively along with a benefit-cost ratio of 2.081, the analysis demonstrates robust economics. Every dollar invested in production generates over two dollars in revenues. Additionally, the high productivity of 0.946 kg biodiesel output per kg of waste cooking oil input signifies an efficient conversion process with minimal losses.

The economic viability of biodiesel production from waste cooking oil, as evidenced by studies conducted across different regions, underscores its potential as a profitable and sustainable alternative to conventional diesel. Despite varying feedstock costs, production expenses, and market prices, all studies unanimously conclude that biodiesel production from waste cooking oil is financially feasible, yielding positive returns on investment.

6. FUTURE PERSPECTIVE

Waste cooking oil has a bright future in the circular economy and sustainable energy. Overcoming challenges and seizing opportunities will be key to achieving their full potential and contributing to a greener and more resource-efficient future. In the future, unlocking the potential of used cooking oils for sustainable energy production and circular economy will be driven by technological advances and expansion of production.

Enhancements in biofuel production methods and waste handling approaches will boost both efficiency and cost-effectiveness over time. In addition, supportive measures at national and international levels will encourage investments and the introduction of initiatives for the recycling of used cooking oils. Integration into circular economy models further optimizes resource use, minimizes waste and maximizes value. Diversifying applications beyond biofuel production, such as bio-plastics and cosmetics, will improve the economics of WCO recycling. Public awareness and education campaigns will play a critical role in promoting widespread adoption, while ongoing research and innovation will drive further advances in technology and applications. Overall, the future prospects are promising, as used cooking oils will make a significant contribution to sustainable energy and environmental protection.

7. CONCLUSION

An innovative approach to achieving a more sustainable and circular energy production involves utilizing waste cooking oils (WCOs) as a raw material for biodiesel. The recycling of WCOs can contribute to the production of environmentally friendly and efficient biodiesel, aligning with the principles of the circular economy. It is a viable replacement for fossil fuels due to its affordability, capacity to fulfil fuel regulations, and lower greenhouse gas emissions. Biodiesel made from WCO is a valuable resource for sustainable energy solutions in global fight against climate change. Although scalability, catalyst development, and purification techniques continue to be obstacles, recent technological developments offer prospects for small-scale distributed production. Demonstrating the viability of biodiesel over conventional biodiesel requires field testing. The ecological footprint is decreased by WCO-based biodiesel, which turns waste into energy. It becomes more appealing within the circular economy due to advancements in pretreatment, catalysts, and process optimization. The optimization of WCO-based biodiesel and the possibility of a cleaner, more circular future are the promises of ongoing research, notwithstanding the obstacles.

ACKNOWLEDGMENT

This research review is indebted to the collective scholarship of authors whose journal articles were meticulously examined. Their valuable insights and contributions have played a crucial role in shaping the comprehensive overview presented in this study. We express our sincere appreciation for their work, which has been pivotal in informing and guiding our review research.

REFERENCES

[1] Nalley, S., & LaRose, A. (2021). International energy outlook 2021, US Department of Energy: Washington, DC, USA. 1-21.

[2] ASTM D6751-08- Standard specification for biodiesel fuel (B100) blend stock for distillate fuels, *In: Annual Book of ASTM Standards*, *ASTM International*, West Conshohocken, Method D6751-08, 2008a.

[3] Ziolkowska, J. R. (2020). Biofuels technologies: An overview of feedstocks, processes, and technologies, *Biofuels for a More Sustainable Future*, 1–19.

[4] Malode, S. J., Gaddi, S. A. M., Kamble, P. J., Nalwad, A. A., Muddapur, U. M., & Shetti, N. P. (2022). Recent evolutionary trends in the production of biofuels, Materials Science for Energy Technologies, 5, 262-277.

[5] Maliha, A., Abu-Hijleh, B. A review on the current status and post-pandemic prospects of third-generation biofuels, *Energy Systems*, 14(4), 1185–1216.

[6] Powar, R. S., Yadav, A. S., Ramakrishna, C. S., Patel, S., Mohan, M., Sakharwade, S. G., Choubey, M., Ansu, A.K, & Sharma, A. (2022). Algae: A potential feedstock for third generation biofuel, *Materials Today: Proceedings*, 63, A27-A33.

[7] Veluru, S., Hamzah, H.T., Tukaram Bai, M, Poiba, V.R. & Mahdi, H.S. (2022). A Review on biodiesel production from various feedstocks by transesterification, IOP *Conf. Series: Materials Science and Engineering*, 1258(1), 012024.

[8] Singh, D., Sharma, D., Soni, S. L., Sharma, S., Kumar Sharma, P. & Jhalani, A. (2019). A review on feedstocks, production processes, and yield for different generations of biodiesel, *Fuel*, 262, 116553.

[9] Paschalidou, A., Tsatiris, M. & Kitikidou, K. (2016). Energy crops for biofuel production or for food? - SWOT analysis (case study: Greece), *Renewable Energy*, 93, 636-647.

[10] Adenuga, A. A., Oyekunle, J. A. O. & Idowu, O. O. (2021). Pathway to reduce free fatty acid formation in Calophyllum inophyllum kernel oil: A renewable feedstock for biodiesel production, *Journal of Cleaner Production*, 316, 128222.

[11] Athar, M. & Zaidi, S. (2020). A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production, *Journal of Environmental Chemical Engineering*, 8(6), 104523.

[12] Awogbemi, O., Von Kallon, D. V., Aigbodion, V. S. & Panda, S. (2021b). Advances in biotechnological applications of waste cooking oil, *Case Studies in Chemical and Environmental Engineering*, 4, 100158.

[13] Khan, H. M., Iqbal, T., Yasin, S., Irfan, M., Kazmi, M., Fayaz, H. & Ullah, N. (2021). Production and utilization aspects of waste cooking oil based biodiesel in Pakistan, *Alexandria Engineering Journal*, 60(6), 5831–5849.

[14] Teixeira, M. R., Nogueira, R. & Nunes, L. M. (2018). Quantitative assessment of the valorisation of used cooking oils in 23 countries, *Waste management*, 78, 611-620.

[15] Yusuff, A. S., Adeniyi, O. D., Olutoye, M. A. & Akpan, U. G. (2018). Waste frying oil as a feedstock for biodiesel production, *in Petroleum Chemicals-Recent Insight, ed. M. Zoveidavianpoor*, IntechOpen, London, UK, 5-24.

[16] Topi, D. (2020). Transforming waste vegetable oils to biodiesel, establishing of a waste oil management system in Albania, *SN Applied Sciences*, 2, 1-7.

[17] Sarno, M., & Iuliano, M. (2019). Biodiesel production from waste cooking oil, *Green Processing and Synthesis*, 8(1), 828-836.

[18] Casallas, I. D., Carvajal, E., Mahecha, E., Castrillon, C., Gomez, H., Lopez, C. & Malagon-Romero, D. (2018). Pre-treatment of waste cooking oils for biodiesel production, *Chemical Engineering Transactions*, 65, 385-390.

[19] Saini, R. D. (2017). Conversion of waste cooking oil to biodiesel, *International Journal of Petroleum Science and Technology*, 11(1), 9-21.

[20] Math, M. C., Kumar, S. P., & Chetty, S. V. (2010). Technologies for biodiesel production from used cooking oil - A review, *Energy for Sustainable Development*, 14(4), 339-345.

[21] Maddikeri, G. L., Pandit, A. B., & Gogate, P. R. (2012). Intensification approaches for biodiesel synthesis from waste cooking oil: a review, *Industrial & Engineering Chemistry Research*, 51(45), 14610-14628.

[22] Statista (2023). Global production of vegetable oils from 2000/01 to 2022/23 (in million metric tons), Statista *Research Department*. https://www.statista.com/statistics/263978/global-vegetable-oil-production-since-2000-2001/. Assessed Online 24/08/2023 at 9.30am

[23] EUBIA - The European Biomass Industry Association (2015). Transformation of used cooking oil into biodiesel: from waste to resource, *Technical Report of European Biomass Industry Association*. 1-8.

[24] Mannu, A., Ferro, M., Pietro, M. E. D., & Mele, A. (2019). Innovative applications of waste cooking oil as raw material, Science Progress, 102(2), 153-160.

[25] Adepoju, T. F., & Olawale, O. (2014). Acid-catalyzed esterification of waste cooking oil with high FFA for biodiesel production, *Chemical and process engineering research*, 21, 80-85.

[26] Foo, W. H., Chia, W. Y., Tang, D. Y. Y., Koay, S. S. N., Lim, S. S., & Chew, K. W. (2021). The conundrum of waste cooking oil: Transforming hazard into energy, *Journal of hazardous materials*, 417(2021), 126129.

[27] Aderibigbe, F. A., Saka, H. B., Mustapha, S. I., Amosa, M. K., Shiru, S., Tijani, I. A., Babatunde, E.O., & Bello, B. T. (2023). Waste Cooking Oil Conversion to Biodiesel Using Solid Bifunctional Catalysts, ChemBioEng Reviews, 10(3), 293-310.
[28] Salihu, A., Mahmood, A. A., Gimba, S. B., Nzerem, P., & Okafor, I. (2021). Production of biodiesel from waste cooking oil by transesterification process using heterogeneous catalyst, Nigerian Journal of Environmental Sciences and Technology (NIJEST) 5(2), 501-510.
[29] Falowo, O. A., Oladipo, B., Taiwo, A. E., Olaiya, A. T., Oyekola, O. O., & Betiku, E. (2022). Green heterogeneous base catalyst from ripe and unripe plantain peels mixture for the transesterification of waste cooking oil, Chemical Engineering Journal Advances, 10, 100293.
[30] Amenaghawon, A. N., Obahiagbon, K., Isesele, V., & Usman, F. (2022). Optimized biodiesel production from waste cooking oil using a functionalized bio-based heterogeneous catalyst, Cleaner Engineering and Technology, 8, 100501.
[31] Linganiso, E. C., Tlhaole, B., Magagula, L. P., Dziike, S., Linganiso, L. Z., Motaung, T. E., Moloto, N., & Tetana, Z. N. (2022). Biodiesel production from waste oils: a South African outlook, Sustainability, 14(4), 1983.
[32] Osagiede, C. A., & Aisien, F. A. (2024). Biochar-based bi-functional catalyst derived from rubber seed shell and eggshell for biodiesel production from waste cooking oil, Fuel, 358, 130076.
[33] Fernandez, C., Bernal, A., Leon, P., Gelves, O., & Malagon-Romero, D. H. (2022). Optimization of a Route for Collecting Waste Cooking Oil in Bogotá, Chemical Engineering Transactions, 91, 625-630.
[34] Tsai, W. T. (2019). Mandatory recycling of waste cooking oil from residential and commercial sectors in Taiwan, *Resources*, 8(1), 38.
[35] Van Grinsven, A., Van den Toorn, E., Van der Veen, R., & Kampman, B (2020). Used Cooking Oil (UCO) as a biofuel feedstock in the EU, Publications of CE Delft, 1-65.
[36] De Feo, G., Di Domenico, A., Ferrara, C., Abate, S., & Sesti Osseo, L. (2020). Evolution of waste cooking oil collection in an area with long-standing waste management problems, Sustainability, 12(20), 8578
[37] Febijanto, I., Ulfah, F. & Trihadi, S. E. Y. (2023). A Review on used cooking oil as a sustainable biodiesel feedstock in Indonesia, *In IOP Conference Series: Earth and Environmental Science*, 1187(1), 012011.
[38] Cárdenas, J., Orjuela, A., Sánchez, D. L., Narváez, P. C., Katryniok, B. & Clark, J. (2021). Pre-treatment of used cooking oils for the production of green chemicals: A review, *Journal of Cleaner Production*, 289, 125129.
[39] Matusinec, J., Hrabec, D., Šomplák, R., Nevrlý, V., & Redutskiy, Y. (2022). Cooking oils and fat waste collection infrastructure planning: a regional-level outline, Clean Technologies and Environmental Policy, 24(1), 109-123.
[40] Loizides, M. I., Loizidou, X. I., Orthodoxou, D. L., & Petsa, D. (2019). Circular bioeconomy in action: collection and recycling of domestic used cooking oil through a social, reverse logistics system, *Recycling*, 4(2), 16.
[41] Susilowati, E., Hasan, A., & Syarif, A. (2019). Free fatty acid reduction in a waste cooking oil as a raw material for biodiesel with activated coal ash adsorbent, *Journal of Physics: Conference Series*, 1167(1), 012035.
[42] Biofuels International. (2021).The conversion of used cooking oils into biodiesel, https:// biofuels-news.com/news/the-conversion-of-used-cooking-oils-into-biodiesel/
[43] Danane, F., Bessah, R., Alloune, R., Tebouche, L., Madjene, F., Kheirani, A.Y., & Bouabibsa, R. (2022). Experimental optimization of Waste Cooking Oil ethanolysis for biodiesel production using Response Surface Methodology (RSM), *Science and Technology for Energy Transition*, 77(14), 1-10.
[44] Kedir, W. M., Wondimu, K. T., & Weldegrum, G. S. (2023). Optimization and characterization of biodiesel from waste cooking oil using modified CaO catalyst derived from snail shell, *Heliyon*, 9(5), 1-13.
[45] Tsoutsos, T. D., Tournaki, S., Paraíba, O., & Kaminaris, S. D. (2016). The Used Cooking Oil-to-biodiesel chain in Europe assessment of best practices and environmental performance, *Renewable and sustainable energy reviews*, 54, 74-83.
[46] Kristiana, T., O'Connell, A., & Baldino, C. (2023). Producing high quality biodiesel from used cooking oil in Indonesia, *ICCT working paper*, 2023-18, 1-15.
[47] Gurdil, G. A. K., Kabutey, A., Selvi, K. Ç., Hrabe, P., Herak, D., & Frankova, A. (2020). Investigation of heating and freezing pretreatments on mechanical, chemical and spectral properties of bulk sunflower seeds and oil, *Processes*, 8(4), 411.
[48] Neuman, T. (2014). Use of separators, decanters in biodiesel processing, Biodiesel Magazine. https://biodieselmagazine.com/articles/use-of-separators-decanters-in-biodiesel-processing-17995 [online: assessed 26th December 2023, 1.20pm]
[49] Ju, J., Zheng, Z., Xu, Y., Cao, P., Li, J., Li, Q. & Liu, Y. (2019). Influence of total polar compounds on lipid metabolism, oxidative stress and cytotoxicity in HepG2 cells, *Lipids in Health and Disease*, 18(1), 1-13.
[50] Foo, W. H., Koay, S. S. N., Tang, D. Y. Y., Chia, W. Y., Chew, K. W., & Show, P. L. (2022). Safety control of waste cooking oil: transforming hazard into multifarious products with available pre-treatment processes, *Food Materials Research*, 2(1), 1-11.
[51] Mamtani, K., Shahbaz, K., & Farid, M. M. (2021). Glycerolysis of free fatty acids: a review, Renewable and *Sustainable Energy Reviews*, 137, 110501.

[52] Ennetta, R., Soyhan, H. S., Koyunoglu, C., & Demir, V. G. (2022). Current technologies and future trends for biodiesel production: a review, *Arabian Journal for Science and Engineering*, 47(12), 15133-15151.
[53] Salaheldeen, M., Mariod, A. A., Aroua, M. K., Rahman, S. A., Soudagar, M. E. M. & Fattah, I. R. (2021). Current state and perspectives on transesterification of triglycerides for biodiesel production, *Catalysts*, 11(9), 1121.
[54] Singh, D., Sharma, D., Soni, S. L., Inda, C. S., Sharma, S., Sharma, P. K, & Jhalani, A. (2021). A comprehensive review of biodiesel production from waste cooking oil and its use as fuel in compression ignition engines: 3rd generation cleaner feedstock, *Journal of Cleaner Production*, 307, 127299.
[55] Saad, M., Siyo, B., & Alrakkad, H. (2023). Preparation and characterization of biodiesel from waste cooking oils using heterogeneous Catalyst (Cat. TS-7) based on natural zeolite, *Heliyon*, 9(6), 1-13.
[56] Degfie, T. A., Mamo, T. T., & Mekonnen, Y. S. (2019). Optimized Biodiesel Production from Waste Cooking Oil (WCO) using Calcium Oxide (CaO) Nano-catalyst, Scientific Reports, 9(1), 18982.
[57] Sakthivel, R., Ramesh, K., Purnachandran, R., & Shameer, P. M. (2018). A review on the properties, performance and emission aspects of the third generation biodiesels, *Renewable and Sustainable Energy Reviews*, 82, 2970-2992.
[58] EN 14214- Committee for Standardization Automotive fuels—fatty acid methyl esters (FAME) for diesel engines—requirements and test methods, European Committee for Standardization, Brussels; 2003a. Method EN 14214.
[59] Wang, B., Wang, B., Shukla, S. K., & Wang, R. (2023). Enabling catalysts for biodiesel production via transesterification, *Catalysts*, 13(4), 740.
[60] Mandari, V., & Devarai, S.K. (2022). Biodiesel Production Using Homogeneous, Heterogeneous, and Enzyme Catalysts via Transesterification and Esterification Reactions: a Critical Review, *Bioenergy Research*, 15, 935–961.
[61] Vilas Boas, R.N., & Mendes, M.F. (2022). A review of biodiesel production from non-edible raw materials using the transesterification process with a focus on influence of feedstock composition and free fatty acids, *Journal of the Chilean Chemical Society*, 67(1), 5433-5444.
[62] Pikula, K., Zakharenko, A., Stratidakis, A., Razgonova, M., Nosyrev, A., Mezhuev, Y., Tsatsakis, A. & Golokhvast, K. (2020). The advances and limitations in biodiesel production: feedstocks, oil extraction methods, production, and environmental life cycle assessment, *Green Chemistry Letters and Reviews*, 13(4), 275-294.
[63] Singh, C. S., Kumar, N., & Gautam, R. (2021). Supercritical transesterification route for biodiesel production: Effect of parameters on yield and future perspectives, *Environmental Progress & Sustainable Energy*, 40(6), e13685.
[64] Neupane, D. (2022). Biofuels from Renewable Sources, a potential option for biodiesel production, *Bioengineering*, 10(1), 1-29.
[65] Gaurav, A., Ng, F. T., & Rempel, G. L. (2016). A new green process for biodiesel production from waste oils via catalytic distillation using a solid acid catalyst–Modeling, economic and environmental analysis, *Green Energy & Environment*, 1(1), 62-74.
[66] Goortani, B. M., Gaurav, A., Deshpande, A., Ng, F. T., & Rempel, G. L. (2015). Production of isooctane from isobutene: energy integration and carbon dioxide abatement via catalytic distillation. *Industrial & Engineering Chemistry Research*, 54(14), 3570-3581.
[67] Pascoal, C. V. P., Oliveira, A. L. L., Figueiredo, D. D., & Assunção, J. C. C. (2020). Optimization and kinetic study of ultrasonic-mediated in situ transesterification for biodiesel production from the almonds of Syagrus cearensis. *Renewable Energy*, 147, 1815-1824.
[68] Moazeni, F., Chen, Y. C., & Zhang, G. (2019). Enzymatic transesterification for biodiesel production from used cooking oil, a review, *Journal of cleaner production*, 216, 117-128.
[69] Bagal, M.V., Shaju, M., Yadav, A., & Chavan, S. (2020). Review: enzymatic tranesterification of waste, *Journal of Emerging Technologies and Innovative Research (JETIR)*, 7(6), 1132-1142.
[70] Patil, P. D., Reddy, H., Muppaneni, T., & Deng, S. (2017). Biodiesel fuel production from algal lipids using supercritical methyl acetate (glycerin-free) technology, *Fuel*, 195, 201-207.
[71] Pal, A., Verma, A., Kachhwaha, S. S., & Maji, S. (2010). Biodiesel production through hydrodynamic cavitation and performance testing, *Renewable Energy*, 35(3), 619-624.
[72] Andreani, L., & Rocha, J. D. (2012). Use of ionic liquids in biodiesel production: a review, *Brazilian Journal of Chemical Engineering*, 29(1), 1-13.
[73] Cheng, J., Mao, Y., Guo, H., Qian, L., Shao, Y., Yang, W., & Park, J. Y. (2022). Synergistic and efficient catalysis over Brønsted acidic ionic liquid [BSO3HMIm][HSO4]–modified metal–organic framework (IRMOF-3) for microalgal biodiesel production, *Fuel*, 322, 124217.
[74] Zhang, Q., Hu, Y., Li, S., Zhang, M., Wang, Y., Wang, Z., & Pan, H. (2022). Recent advances in supported acid/base ionic liquids as catalysts for biodiesel production, *Frontiers in Chemistry*, 10, 999607.
[75] Gholami, A., Pourfayaz, F., & Maleki, A. (2020). Recent advances of biodiesel production using ionic liquids supported on nanoporous materials as catalysts: a review, *Frontiers in Energy Research*, 8, 144.
[76] Troter, D. Z., Todorović, Z. B., Đokić-Stojanović, D. R., Stamenković, O. S., & Veljković, V. B. (2016). Application of ionic liquids and deep eutectic solvents in biodiesel production: A review, *Renewable and Sustainable Energy Reviews*, 61, 473-500.
[77] Liu, C. Z., Wang, F., Stiles, A. R., & Guo, C. (2012). Ionic liquids for biofuel production: opportunities and challenges, *Applied energy*, 92, 406-414.

[78] Ramadhan, A.R., Pornwongthong, P., Rattanaporn, K., & Sriariyanun, M. (2015). Review of Ionic Liquid as a Catalyst for Biodiesel Production, *Journal of Science and Technology MSU*, 34(4), 404-412.
[79] Chintagunta, A.D., Zuccaro, G., Kumar, M., Kumar, S. J., Garlapati, V.K., Postemsky, P.D., Sampath Kumar, N.S., Chandel, A.K., & Simal-Gandara, J. (2021). Biodiesel production from lignocellulosic biomass using oleaginous microbes: prospects for integrated biofuel production, *Frontiers in Microbiology*, 12, 1-23.
[80] Shi, S., Valle-Rodríguez, J. O., Siewers, V., & Nielsen, J. (2011). Prospects for microbial biodiesel production, *Biotechnology journal*, 6(3), 277-285.
[81] Sharma, A., Kodgire, P., & Kachhwaha, S. S. (2019). Biodiesel production from waste cotton-seed cooking oil using microwave-assisted transesterification: Optimization and kinetic modeling, *Renewable and Sustainable Energy Reviews*, 116, 109394.
[82] Nayak, S. N., Bhasin, C. P., & Nayak, M. G. (2019). A review on microwave-assisted transesterification processes using various catalytic and non-catalytic systems, *Renewable Energy*, 143, 1366-1387.
[83] El Sherbiny, S. A., Refaat, A. A., & El Sheltawy, S. T. (2010). Production of biodiesel using the microwave technique, *Journal of Advanced Research*, 1(4), 309-314.
[84] Palma, V., Barba, D., Cortese, M., Martino, M., Renda, S. & Meloni, E. (2020). Microwaves and heterogeneous catalysis: A review on selected catalytic processes, *Catalysts*, 10(2), 246.
[85] Martinez-Guerra, E., & Gude, V. G. (2015). Continuous and pulse sonication effects on transesterification of used vegetable oil, *Energy Conversion and Management*, 96, 268-276.
[86] Riyanto, T., Istadi, I., Buchori, L., Anggoro, D. D., & Dani Nandiyanto, A. B. (2020). Plasma-assisted catalytic cracking as an advanced process for vegetable oils conversion to biofuels: A mini review, *Industrial & Engineering Chemistry Research*, 59(40), 17632-17652.
[87] Cubas, A. L. V., Machado, M. M., Pinto, C. R. S. C., Moecke, E. H. S., & Dutra, A. R. A. (2016). Biodiesel production using fatty acids from food industry waste using corona discharge plasma technology, *Waste management*, 47, 149-154.
[88] Karki, S., Sanjel, N., Poudel, J., Choi, J. H., & Oh, S. C. (2017). Supercritical transesterification of waste vegetable oil: characteristic comparison of ethanol and methanol as solvents, *Applied Sciences*, 7(6), 632.
[89] Kulkarni, M. G., & Dalai, A. K. (2006). Waste cooking oil an economical source for biodiesel: a review, *Industrial & engineering chemistry research*, 45(9), 2901-2913.
[90] Okoro, O. V., Sun, Z., & Birch, J. (2018). Catalyst-free biodiesel production methods: A comparative technical and environmental evaluation, *Sustainability*, 10(1), 1-22.
[91] Oliveira, P. A., Baesso, R. M., Moraes, G. C., Alvarenga, A. V., & Costa-Félix, R. P. (2018). Ultrasound methods for biodiesel production and analysis, *Biofuels-State of Development*, 121-148.
[92] Oliveira, P. A., Baesso, R. M., Morais, G. C., Alvarenga, A. V., & Costa-Félix, R. P. (2021). Ultrasound-assisted transesterification of soybean oil using low power and high frequency and no external heating source, *Ultrasonics Sonochemistry*, 78(2021), 1-9.
[93] Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm? *Journal of cleaner production*, 143, 757-768.
[95] Cho, S., Kim, J., Park, H. C., & Heo, E. (2015). Incentives for waste cooking oil collection in South Korea: a contingent valuation approach, *Resources, Conservation and Recycling*, 99, 63-71.
[96] Alias, N. I., Jayakumar, J. K., & Zain, S. M. (2018). Characterization of waste cooking oil for biodiesel production, *Jurnal Kejuruteraan*, 1(2), 79-83.
[97] Ganesan, K., Sukalingam, K., & Xu, B. (2019). Impact of consumption of repeatedly heated cooking oils on the incidence of various cancers- A critical review, *Critical Reviews in Food Science and Nutrition*, 59(3), 488-505.
[98] Lopes, M., Miranda, S. M., & Belo, I. (2020). Microbial valorization of waste cooking oils for valuable compounds production–a review, *Critical Reviews in Environmental Science and Technology*, 50(24), 2583-2616.
[99] United Nations General Assembly. (2015). Transforming our world: the 2030 agenda for sustainable development (A/RES/70/1). Retrieved from https://sustainabledevelopment.un.org/post2015/transformingourworld
[100] Gebremariam, S. N., & Marchetti, J. M. (2018). Economics of biodiesel production, *Energy Conversion and* 660 *Management*, 168, 74-84.
[101] Karmee, S. K., Patria, R. D., & Lin, C. S. K. (2015). Techno-economic evaluation of biodiesel production from waste cooking oil—a case study of Hong Kong, *International journal of molecular sciences*, 16(3), 4362-4371.
[102] Keera, S. T., El Sabagh, S. M., & Taman, A. R. (2011). Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst, *Fuel*, 90(1), 42-47.
[103] Avinash, A., & Murugesan, A. (2017). Economic analysis of biodiesel production from waste cooking oil, *Energy Sources, Part B: Economics, Planning, and Policy*, *12*(10), 890-894.
[104] Mohammadshirazi, A., Akram, A., Rafiee, S., & Kalhor, E. B. (2014). Energy and cost analyses of biodiesel production from waste cooking oil. Renewable and sustainable energy reviews, 33(1), 44-49.