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Review

An extensive examination of the potential of waste cooking oil biodiesel in Bangladesh

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ABSTRACT

Waste cooking oil (WCO) has gained attention as a valuable resource for biodiesel production due to its availability and potential for waste management. This study examines the viability of WCO as a biodiesel feedstock in Bangladesh, addressing the increasing demand for sustainable energy alternatives. This paper explores multiple facets of WCO biodiesel, encompassing feedstock types, pretreatment techniques, and the production process. The study analyzes the physicochemical properties, emission characteristics, performance, and combustion behavior of biodiesel derived from WCO. The findings indicate that WCO biodiesel presents considerable potential as an economically viable and environmentally sustainable alternative fuel for diesel engines in Bangladesh. Challenges in WCO collection, commercialization, and public awareness must be addressed to realize its full potential. The paper concludes by proposing avenues for further research in Bangladesh, emphasizing the enhancement of collection systems, the refinement of policy frameworks, and the optimization of conversion technologies to facilitate the broader adoption of WCO biodiesel.

1. Introduction

The rapid industrialization and urbanization that have occurred since the mid-20th century have driven the global surge in diesel production, providing the backbone for transportation, energy generation, and industrial operations [1]. Although diesel has played a crucial role as a fuel source, its associated environmental and economic issues, such as greenhouse gas emissions, pollution, and resource depletion, have ignited a global quest for sustainable alternatives. Carbon dioxide (CO_2) is the primary contributor to global warming, increasing from roughly 3.34 million tons in 1970 to around 124.79 million tons in 2023. In 2022, global energy-related CO_2 emissions totaled approximately 36.8 gigatons, representing a 0.9% increase from the previous year. In 2022, the transportation sector contributed nearly eight gigatons of CO_2 emissions, representing approximately 23% of global energy-related CO_2 emissions [2]. The ongoing dependence on fossil fuels, particularly diesel, has intensified environmental degradation through air pollution and climate change, while also raising concerns about resource depletion and energy security. Crude oil reserves are expected to be depleted by 2052, given the current annual consumption rate of 4 billion tons [3]. This projection indicates a looming energy crisis if alternative solutions are not adopted promptly. Bangladesh's energy sector is heavily reliant on fossil fuels, with more than 85% of electricity generation coming from conventional sources, predominantly natural gas, which accounts for over 50% of annual electricity production [4]. Even with a rise in electricity generation to support industrial expansion, the nation faces challenges stemming from dwindling fossil fuel reserves and insufficient oil resources, necessitating expensive imports [5]. The rising global fuel prices, geopolitical conflicts, and supply chain disruptions further strain Bangladesh's energy security, prompting efforts to explore alternative energy solutions. Additionally, the country's rapid industrialization and urbanization have led to a surge in CO_2 emissions, with fossil fuel combustion contributing significantly to environmental degradation. Bangladesh's per capita CO_2 emissions have risen from approximately 0 tons in 1946 to 0.7 tons in 2023 [6]. In 2021, fuel combustion resulted in the emission of 17.17 million tons of CO_2, positioning Bangladesh as the 13th highest emitter in the Asia-Pacific region in terms of carbon emissions [7]. Despite accounting for only 0.09% of global carbon emissions, Bangladesh is significantly vulnerable to climate change, ranking eighth on the 2021 Global Climate Risk Index [8]. The government has pledged to reduce emissions by 21.8% by 2030, in line with the Paris Agreement, underscoring the urgent need for a transition to renewable energy sources [9]. The currently available number of renewables, particularly solar energy, hovers between 2-4%, highlighting the necessity for legislative reforms, financial incentives, and technological improvements to minimize reliance on fossil fuels and foster sustainable energy alternatives [10]. Facing the threat of declining fossil fuel reserves and potential energy crises, nations worldwide are increasingly exploring a variety of alternative energy sources [11]. Bioethanol, biomethanol, biobutanol, biogas, and biodiesel have emerged as promising alternatives to fossil fuels, offering renewable and environmentally friendly energy sources. Bioethanol, sourced from agricultural feedstocks, demonstrates energy balance and enhances combustion efficiency; however, it is notably corrosive and necessitates modifications to engines [12]. Biomethanol, recognized for its biodegradability and compatibility with the current petrol distribution infrastructure, encounters obstacles stemming from its toxicity and the necessity for elevated temperature conditions [13]. Biobutanol, a multifaceted biofuel, can be utilized directly in gasoline engines without necessitating modifications. It offers a high energy content; however, its production is challenging, and it has a reduced heating value compared to gasoline [14]. Biogas, produced from plant and animal waste, is a cost-effective and sustainable fuel that reduces greenhouse gas emissions, yet its high impurity content necessitates additional refining processes [15]. Biodiesel, currently the most widely recognized alternative, is recognized for its low sulfur emissions, non-toxic characteristics, and ability to reduce particulate matter in diesel engines. Nonetheless, it presents certain challenges, such as heightened viscosity, which affects the efficiency of fuel injection. Despite showing great promise in addressing energy security and sustainability challenges, their inherent limitations necessitate further technological advancements to enable large-scale adoption.

Biodiesel production continues to grow worldwide, with Europe leading both output (34%) and consumption (35%). However, raw feedstock costs—constituting up to 80% of total production expenses—remain a significant barrier [16]. Since approximately 95% of the world's biodiesel relies on edible oils, the resulting increase in raw material prices has made biodiesel 1.5 to 2 times more expensive than diesel [17]. This escalation hinders commercial viability and spurs interest in alternative feedstocks such as non-edible oils and waste cooking oil (WCO), which can potentially lower production costs by up to 70% [18]. In Bangladesh, where an estimated 1-1.2 lakh tons of WCO is generated annually, only a small fraction is properly managed; the majority is black-marketed or reused in restaurants, contrary to the country's Food Safety Act [19]. Such practices pose serious health and environmental risks, yet the abundance of WCO presents a cost-effective option for biodiesel production, especially amid rising edible oil prices [20]. Recent efforts by local and international companies to collect and convert WCO into biodiesel underscore its promise as an advanced biofuel feedstock, highlighting the potential for both environmental and economic benefits. Hence, the focus of this paper is to examine WCO-based biodiesel within the Bangladeshi context and explore strategies for its sustainable large-scale implementation.

2. Biodiesel and its feedstock

Biodiesel is a renewable alternative fuel produced through transesterification, where oils or fats react with alcohol (usually methanol) in the presence of a catalyst to form fatty acid methyl esters (FAME), which are biodiesel [21]. The advantages of biodiesel include its biodegradability, non-explosiveness, non-flammability, and non-toxicity, alongside the crucial benefit of being renewable [22]. The feedstocks for biodiesel can be categorized into four generations, shown in Figure 1, with each offering distinct benefits and challenges.

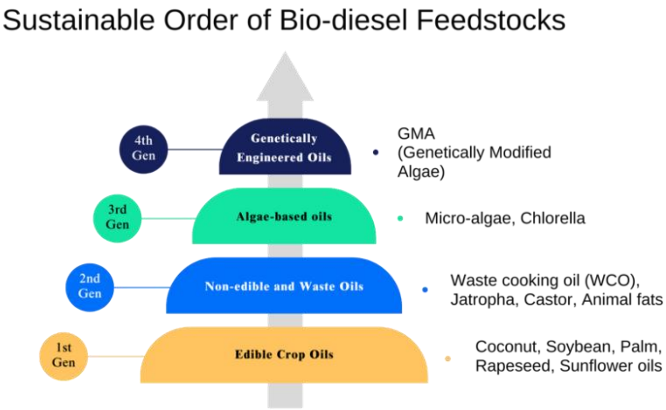

Figure 1. Generation of biodiesel feedstock

2.1 First-generation feedstocks (1G)

First-generation feedstocks include edible oils like palm oil, soybean oil, sunflower oil, and rapeseed oil, which are commonly used for biodiesel production due to their high oil content and availability [23]. However, their use has led to the "food vs. fuel" debate, as they compete with food crops, raising the cost of biodiesel production.

2.2 Second-generation feedstock (2G)

Second-generation feedstocks, such as Jatropha, Jojoba, Neem, and Waste Cooking Oil (WCO) are derived from non-edible oils that do not compete with food production [24]. While these oils help mitigate the food vs. fuel issue, their cultivation still requires significant land, which could otherwise be used for food crops [25]. However, some non-edible oils, like Jatropha, can be grown on marginal lands, reducing the pressure on arable land [26]. WCO, in particular, reduces biodiesel production costs by up to 70–80% and prevents environmental pollution [27]. However, WCO requires pretreatment due to its high impurity content [28].

2.3 Third-generation feedstock (3G)

Third-generation feedstocks, such as microalgae and animal fats, offer significant potential for biodiesel production due to their low cost and availability [29]. Microalgae, with high lipid content and rapid growth, also hold promise but face challenges in large-scale cultivation due to high nutrient demands and land requirements.

2.4 Fourth-generation feedstock (4G)

Fourth-generation feedstocks, such as electro-fuels and solar fuels, are an emerging area of research in biodiesel production [30]. These feedstocks offer the potential for high lipid content and superior CO_2 absorption, contributing to sustainability. However, they are still in the early stages of development, and the main challenge lies in making their production economically viable at a large scale [31].

3. Waste cooking oil (WCO) production

Waste cooking oil (WCO) is produced from repeatedly used edible oils, which increases impurities such as free fatty acids (FFAs) and water, necessitating pretreatment before biodiesel production [32]. Globally, large quantities of WCO—running into millions of tons—underscore its potential as a cheap, non-food feedstock [33]. In Bangladesh, annual edible oil consumption exceeds 20 lakh tons, with discarded oil often reused or disposed of improperly, posing health and environmental threats [34]. Converting WCO into biodiesel can significantly cut production costs, avert reintroduction into the food chain, and reduce waste. Companies like Muenzer Bangla exemplify this potential by collecting WCO from restaurants and transforming it into cleaner energy, marking a promising path toward sustainable fuel solutions in Bangladesh [35].

4. Pretreatment of WCO

Removing impurities, free fatty acids (FFA), and water from waste cooking oil (WCO) is crucial for efficient biodiesel production [36]. High FFA can cause saponification, lowering biodiesel yield and increasing catalyst consumption. Common techniques include acid esterification with methanol and sulfuric acid, neutralization with alkalis, and heating above 100 °C or vacuum distillation to eliminate water. Additionally, filtration and centrifugation help remove solids and phospholipids.

5. Biodiesel production from WCO

Biodiesel can be produced from waste cooking oil (WCO) using several distinct processes, including gasification, catalytic pyrolysis, hydrocracking [37], and fast pyrolysis [38]. Having said that, transesterification is the most widely used and practical method due to its effectiveness and low cost. One of the key benefits of biodiesel is its ability to be blended with conventional diesel in different ratios, such as B5 (5% biodiesel and 95% diesel) or B20 (20% biodiesel and 80% diesel), making it a viable alternative for fueling internal combustion engines [39]. Biodiesel has approximately 9% less energy content than conventional diesel [40]; yet, it is frequently preferred for its enhanced combustion characteristics and significantly reduced emissions, making it an ecologically sustainable option.

5.1 Transesterification

The transesterification, also known as methanolysis, process involves reacting triglycerides (fats and oils) with alcohol (usually methanol) in the presence of a catalyst to produce biodiesel (fatty acid methyl esters, FAMEs) and glycerol as by-products [41].

This method is preferred for large-scale biodiesel production because it requires minimal modifications to diesel engines and integrates easily into existing industrial systems. The process occurs in three consecutive reversible reactions: triglycerides are first converted to diglycerides, then to monoglycerides, and finally to glycerol, with each step producing an ester. This results in three ester molecules from one triglyceride [42]. When methanol is used, the product is methyl esters (FAMEs), while ethanol produces ethyl esters (FAEEs). The reaction is typically catalyzed by inorganic catalysts like KOH or NaOH, which accelerate the process and improve the yield. The general chemical equation for this reaction is shown in Figure 2 and Figure 3.

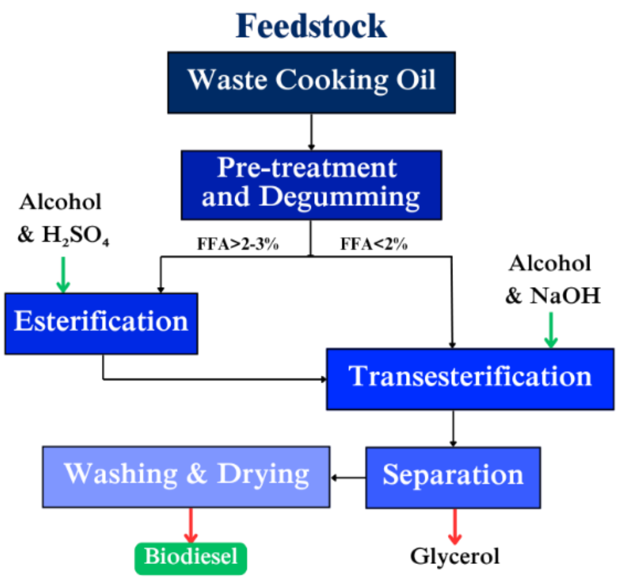

Figure 2. Flow diagram of biodiesel production from WCO

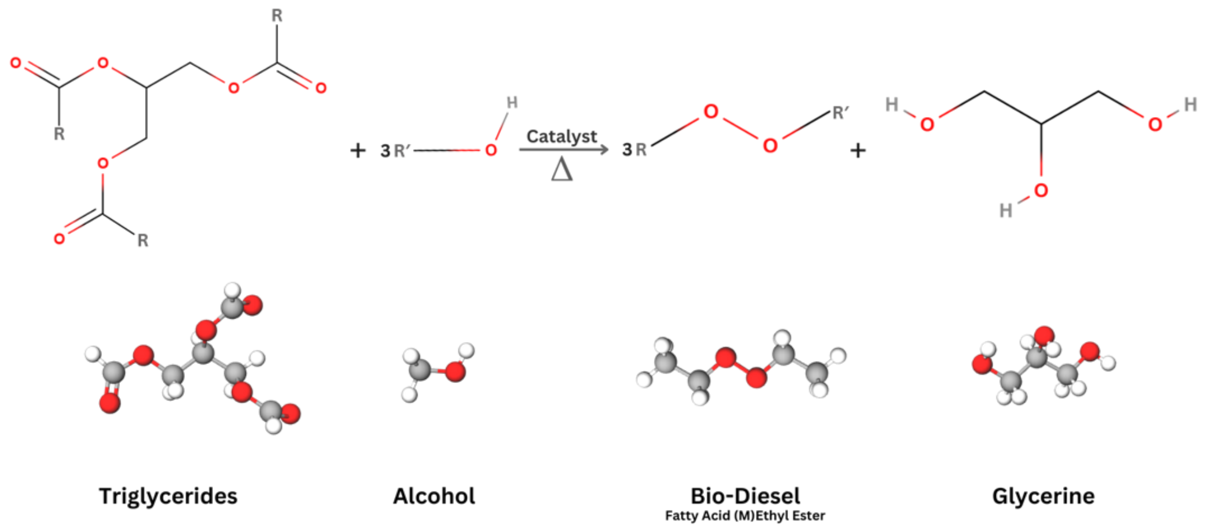

Figure 3. General transesterification reaction

6. Physicochemical properties of WCO

WCO–based biodiesel exhibits several key physicochemical properties that impact its suitability for compression ignition engines. These properties are influenced by free fatty acid content, production methods (e.g., transesterification conditions), and purification steps [43]. Below is a brief overview of major properties—namely, kinematic viscosity, density, cetane number, flash point, cloud point, pour point, acid value, and higher heating value—as gleaned from the literature. Table 1 presents a comparative analysis of the physicochemical properties of WCO, as reported by various authors.

6.1 Density

Density plays a pivotal role in injection mass flow. WCO biodiesel generally has a higher density than petro-diesel. This is attributed to the presence of saturated and unsaturated fatty acids [44]. Overly high densities (e.g., >880 kg/m^3) may increase brake-specific fuel consumption, while blending with diesel or removing impurities can mitigate this issue [45].

6.2 Kinematic viscosity

Kinematic viscosity critically affects fuel injection, spray atomization, and overall combustion efficiency. WCO biodiesel often displays higher viscosity than mineral diesel [32]. If viscosity is excessive, larger fuel droplets form, leading to incomplete combustion and potential deposit buildup. However, viscosity that is too low can reduce lubricity and harm the injection system. Most studies report that properly produced WCO biodiesel falls between 4–5 mm^2/s at 40 °C, in line with ASTM D445 standards [45]. EN ISO 3104 (3.5 mm^2/s to 5.0 mm^2/s) and ASTM D445 (1.9 mm^2/s to 6.0 mm^2/s) are employed to assess the viscosity of biodiesel [46].

6.3 Pour point

Pour point is the lowest temperature at which the fuel remains pourable. High pour points are common in WCO biodiesel, especially if the source oil contains elevated saturated fat content (e.g., palm-derived WCO) [47]. This property can pose challenges in colder climates [48]. Typical improvement strategies include blending with lower-viscosity fuels or adding pour-point depressants [49].

6.4 Flash point

Flash point indicates the temperature at which fuel vapors ignite [50]. WCO biodiesel typically exhibits a higher flash point than diesel [51], enhancing transport and storage safety. Yet residual alcohol from transesterification can reduce flash points below the ASTM minimum (100 °C), emphasizing the need for thorough processing [52].

6.5 Cloud point

The cloud point is the temperature at which wax crystals emerge, posing potential blockages in filters or injectors under cold conditions [45]. Due to the presence of saturated fatty acids, many WCO biodiesels do not meet the ASTM-recommended sub-zero cloud point [44].

6.6 Iodine number

Iodine number signifies the degree of unsaturation in the fatty acid chains constituting biodiesel. A higher iodine number implies more double bonds, which can influence oxidative stability and cold-flow behavior [53]. WCO feedstocks that contain greater amounts of unsaturated fatty acids tend to produce biodiesel with elevated iodine numbers [54].

6.7 Cetane number

The cetane number measures ignition quality; higher values translate into shorter ignition delays and improved cold starting [55]. Most WCO biodiesel samples exhibit cetane numbers of≥47 [44], which meet the ASTM D6751 guidelines.

6.8 Higher Heating Value (HHV)

The higher heating value represents the total energy content of the fuel. WCO biodiesel typically shows an HHV around 39 MJ/kg, slightly lower than petroleum diesel (~43 MJ/kg) [56]. Consequently, engines may consume a marginally greater volume of WCO biodiesel for the same power output, though the difference is often acceptable for most CI applications.

6.9 Acid value

Acid value reflects free fatty acids and oxidation byproducts [57]. Exceeding ~0.5 mg KOH/g can promote corrosive effects and fuel instability [58]. Pre-treatment steps such as esterification and subsequent purification are therefore crucial to bring acid values within ASTM limits [59].

7. Types of catalysts

Catalysts are essential for enhancing the transesterification process, playing a key role in determining the efficiency, cost, and reaction time of biodiesel production. Based on their physical state and chemical properties, these catalysts are broadly categorized into homogeneous and heterogeneous types [66]. Homogeneous catalysts, including both acids and bases, are widely used due to their high activity and simple reaction setups, while heterogeneous and enzymatic catalysts offer benefits such as reusability and environmental compatibility. Figure 4 illustrates the main types of transesterification catalysts, and Table 2 compares their effectiveness under various reaction conditions.

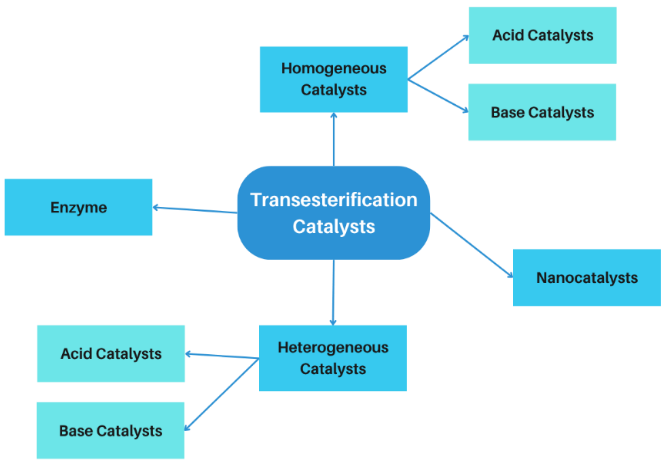

Figure 4. Types of catalysts for transesterification

8. Emission characteristics

Biodiesel produced from waste cooking oil (WCO) has garnered considerable interest as a sustainable substitute for traditional diesel fuel. The emission characteristics, specifically regarding CO_x, NO_x, unburned hydrocarbons (HC), and particulate matter (PM), have been thoroughly examined [92].

Table 1. Comparison of physicochemical properties

Property	Unit	Diesel	WCO					
Density (15-20° C)	Kg/m^3	828.54	871	874	865	880	881	884
Kinematic Viscosity (40° C)	cSt	2.7	4.3	3.69	4.18	6	3.58	4.95
Pour Point	° C	-37	2	-3.4	-4.5	-3	-8.4	-6
Flash point	° C	65	133	175	202	140	170	178
Cloud point	° C	-5	6	1.6	1	-1	-1.43	0
Iodine Value	g I_2/100 g	-	66.52	-	-	33	128.4	146.44
Cetane Number	CI	54.1	46	70.24	-	56.67	44.315	49.14
Higher Heating Value	MJ/kg	43.386	37.4	44.13	39.48	41.4	-	37.114
Acid Value	mmg KOH/g	0.2	0.92	0.39	0.3	0.8	-	0.48
Ref.		[60]	[61]	[62]	[63]	[64]	[65]	[60]

Table 2. Comparison of physicochemical properties

Types of Catalyst	Catalyst	Methanol to Oil ratio	Reaction Conditions		FAME (%)	Reference
			Temperature	Time		
Homogeneous base catalyst	KOH	6:1	65 ◦ C	1 h	93.2	[67]
	NaOH	12:1	65 ◦ C	0.03 h	98.2	[68]
	CH_3ONa	3.9:1	120 ◦ C	6 h	91	[69]
	CH_3OK	6:1	60 ◦ C	0.5 h	99	[70]
Homogeneous acid catalyst	H_2SO_4	245:1	70◦ C	4 h	99	[71]
Heterogeneous base catalyst	CaO	3.5:1	130 ◦ C	1.5 h	94	[72]
	MgO	24:1	65 ◦ C	1 h	93.3	[73]
	MgO-NaOH	6:1	50 ◦ C	6 h	97	[74]
	SrO	9:1	65 ◦ C	0.07 h	93	[75]
	K3PO4	6:1	60 ◦ C	2 h	97.3	[76]
	α-Fe_2O_3-Al_2O_3	15:1	65 ◦ C	3 h	87.78	[77]
Heterogeneous acid catalyst	ZS/Si	18:1	200◦ C	10 h	98	[78]
	RS-SO_3H	18:1	70 ◦ C	1 h	90.38	[79]
	ZrHPW	20:1	65 ◦ C	8 h	98.9	[80]
	SHER	12:1	60 ◦ C	2 h	97	[81]
	Fe-Al-TiO_2	10:1	90 ◦ C	2.5 h	96	[82]
Enzyme	Candida Antarctica Lipase B	4:1	40 °C	30 h	96	[83]
	Geotrichum candidum	1.15:1	40 °C	1.33 h	94.1	[84]
	Immobilized Penicillium	1:1	35 °C	7 h	92.8	[85]
	Pseudomonas cepacia	6.6:1	38.4 °C	2.47 h	96	[86]
Bifunctional	CaO/Fe_2O_3	18:1	65 ◦ C	3 h	98.3	[87]
	CaO/Al_2O_3	12:1	60 ◦ C	3 h	98.23	[88]
	Fly ash/CaO, SO_3	3.1:1	59 °C	6 h	100	[89]
	Sn/CaO	16.1:1	85.15 ◦ C	3.42 h	97.39	[90]
	TiO_2/PrSO_3H	15:1	60 ◦ C	9 h	98.3	[91]

Its oxygen content improves combustion efficiency, typically reducing carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) when compared to diesel. Table 2 summarizes the emission findings documented by multiple researchers.

8.1 CO_x emission

CO emissions generally decrease with WCO biodiesel, benefiting from its higher oxygen content [93]. CO_x emissions may either stay similar or increase, depending on combustion efficiency and blend ratio [94]. CO_2 emissions from WCO biodiesel can be higher or similar to those from diesel, depending on the combustion efficiency and blend ratio [95]. Enhanced oxidation typically leads to higher CO_2 emissions, although some studies report only moderate differences [96].

8.2 NO_x Emissions

Increased WCO biodiesel usage typically leads to higher NO_x emissions, attributed to the fuel's higher oxygen content and increased combustion temperatures. Advanced injection timing and higher bulk modulus may exacerbate NO_x levels, though mitigation strategies like exhaust gas recirculation have proven effective. NO_x emissions often increase with higher biodiesel content, likely due to elevated in-cylinder temperatures and changes in ignition timing.

8.3 Unburned HC and PM

HC emissions typically decrease with WCO biodiesel, due to better combustion. PM and smoke opacity also reduce, especially under higher load conditions, where soot oxidation improves. However, some studies report minimal or increased PM at low loads or specific conditions [97].

The reduced calorific value, increased viscosity, and increased density of WCO biodiesel affect Brake Thermal Efficiency (BTE), Brake-Specific Fuel Consumption (BSFC), and Brake Power (BP), according to numerous studies. However, the use of additives and the optimization of engine parameters have shown promise in mitigating these drawbacks and, in some cases, enhancing performance. Table 3 collates the findings from multiple studies.

9.1 Brake thermal efficiency (BTE)

Brake Thermal Efficiency (BTE) indicates the effectiveness with which an engine transforms the chemical energy of gasoline into mechanical work. Numerous studies demonstrate that waste cooking oil (WCO) biodiesel and its blends typically produce a somewhat reduced BTE relative to petroleum diesel, chiefly due to their diminished calorific value and increased viscosity. Some authors report modest BTE reductions of about 1–2% at higher loads or higher biodiesel blend ratios.

9.2 Brake-specific fuel consumption (BSFC)

BSFC serves as an essential metric that reflects the quantity of fuel utilized per unit of brake power (kW) over the span of one hour. A prevalent observation in the literature indicates that WCO biodiesel demonstrates a greater BSFC in comparison to diesel. The primary factors involve the reduced heating value, increased density, and elevated viscosity of WCO biodiesel, which require a marginally greater fuel mass injection to attain equivalent power output. Certain studies indicate that there are increases in BSFC within the range of 2–17%. While others have observed more pronounced rises at specific loads or for higher blends.

Table 3. Comparison of emission characteristics

Oil	Blend	CO	CO_2	NO_x	HC	PM	Ref.
WCMO	B100	Significant reduction	-	Gradual Increase	Significant Reduction	Vast Reduction in Smoke	[98]
WCO	B100	Up to 58.9% Reduction	Up to 8.6% reduction	Up to 37.5% reduction	-	-	[99]
WCO	B100	Slightly lower	-	Increased	Slightly lower	Significantly reduced	[92]
WCO	B100	8.59% reduction	2.62% increase	5.03% increase	30.66% reduction	63.33% reduction	[100]
WCO (Coconut)	B5	7.3% reduction	-	1% reduction	23% reduction	-	[101]
WCO	B100	17.14% reduction	8.05% reduction	1.45% reduction	-	-	[102]
WCO	B100	Significant decrease	-	Slight increase	Significant decrease	Sharp reduction	[103]
WCO	B100	7% reduced	-	-	Lower	-	[104]
WCO	B100	-	-	Higher	Lower	-	[105]
WCO	B100	Decreased	-	Increased	Decreased	-	[106]
WCO	B100	Reduced	-	Higher	Reduced	Reduced	[107]
WCMO	B100	111% reduced	12% increased	9% increased	600% decreased	-	[108]
WCO	B100	Minimum	Minimum	Unreliable	Minimum	-	[109]
WCO	B100	24.76% decreased	-	15.67% increased	22.95% decreased	48.13% decreased	[97]

Interestingly, a few studies point to optimized blends (e.g., B40) or additive use (nanoparticles) mitigating the BSFC penalty [110]. One notable exception to this rule of thumb is the finding that biodiesel has a lower BSFC than diesel, put out by Altun et al. [111]. This raises questions about the validity of the results and may indicate the presence of an unusual experimental design or a statistical outlier.

9.3 Brake power (BP)

Brake Power (BP) is fundamentally influenced by the calorific value of the fuel as well as the quality of the air-fuel mixture. The reduced energy density of WCO biodiesel may result in diminished brake power output in comparison to diesel. Decreases in BP or torque are frequently associated with a rise in the proportion of WCO biodiesel within the blend. The power loss is negligible, however, for low or moderate blend levels and lower engine speeds, according to some experimental study [112]. Engine adjustments, such as altering injection pressure or timing, can also help to make up for some of the power disadvantage [113].

10. Combustion characteristics

The combustion properties of waste cooking oil (WCO) biodiesel, such as ignition delay, peak pressure, and heat release, vary from those of diesel [120]. WCO blends demonstrate reduced ignition delays attributable to their elevated cetane number and oxygen content, which improve combustion. Due to improved combustion, WCO blends have a slightly greater peak pressure than diesel. However, the rate of pressure rise is lower since there is less fuel accumulation during the ignition delay. While WCO blends have a lower calorific value and hence a slower heat release rate, the higher oxygen concentration improves combustion efficiency at higher speeds.

11. Conclusion

This research emphasizes the viability of waste cooking oil as a sustainable and cost-effective feedstock for Bangladesh. The key findings of the study are as follows: Waste cooking oil serves as a viable and economical feedstock for biodiesel production in Bangladesh, with an annual availability surpassing one hundred thousand tons. WCO biodiesel typically complies with international physicochemical property requirements, encompassing acceptable limits for viscosity, density, and cetane number.
WCO is an optimal feedstock for the production of biodiesel due to its ability to produce a significant quantity of FAME under optimal transesterification conditions, regardless of the type of catalyst used. The combustion of WCO biodiesel results in a reduction of hazardous emissions, including carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM), as compared to diesel. Despite these benefits, it presents certain trade-offs, including slightly reduced brake thermal efficiency (BTE), higher brake-specific fuel consumption (BSFC), and elevated NOx emissions. The findings indicate that WCO biodiesel is not technically viable; nevertheless, it is significantly pertinent to Bangladesh's energy and environmental requirements. Its use provides a dual advantage, such as functioning as a renewable energy source while also delivering an effective solution for managing waste cooking oil. Large-scale use could minimize production costs, reduce pollution, and prevent the harmful usage of WCO in the food chain. Moreover, it fulfils Bangladesh's commitments regarding climate change under the Paris agreement and decreases dependency on costly fossil fuel imports, hence improving national energy security. Future research should focus on developing practical and economical collection networks, enhancing pretreatment procedures, and advancing conversion technologies. In addition, continuous investigations into advanced catalysts, optimal blending techniques, and engine modifications are necessary to overcome performance limitations and ensure that WCO biodiesel becomes a feasible and sustainable contributor to Bangladesh's clean energy transition.

Table 4. Comparison of performance characteristics

Reference	Oil Blend	BTE	BSFC	BP	Load Condition
[114]	WCO	Similar to diesel	Similar to diesel	-	Different loads, constant speed
[105]	WCO Pure	~1–1.5% efficiency loss at higher loads vs. diesel	Higher than diesel at a higher speed	Slightly lower than diesel	Various loads
[115]	WCO B100	~6% lower than diesel	~10% higher than diesel	-	Maximum load
[116]	WCO Pure	Almost similar to diesel	~17.8% higher than diesel	-	Full Load
[60]	WCO Pure	~11.5% drop	~ 28.67% increased	~34.5% drop	0.16–0.65 MPa
[104]	WCO Pure	~1.5% higher than diesel	~11.6% ↑ than diesel	~13% lower than diesel	Various loads
[117]	WCO B40	Slightly higher	Lower than diesel	Comparable to diesel	Various loads, varying compression
[118]	WCO B100	~14.2% increase than diesel	~3% higher than diesel	5.56% drop in power	-
[111]	WCO	-	Lower for WCO than diesel	Lower torque than diesel	-
[119]	WCO B10	~6.45% decreased	~3.3% increased	~3.8% lower than diesel	Various loads

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Ethical issue
The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement
The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest
The authors declare no potential conflict of interest.

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