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Agro-residue bio-oil emulsions in CI engines: A critical review of combustion and emission characteristics

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Abstract
Compression ignition (CI) engines are widely used in transport, industry, and agriculture due to their high thermal efficiency and strong torque generation capability. With depleting fossil fuel reserves and stringent emission regulations, interest in alternative fuels is increasing. Non-conventional fuels offer environmental benefits and improved combustion characteristics and are therefore considered essential for future CI engine development. Second-generation liquid fuels could be produced as second yield of bio-oil from pyrolysis of agricultural residues. Moreover, pyrolysis also generates two other by-products: biochar and syngas. The conversion of these biomass residues into bio-oils, biochar and syngas, therefore, supports the principles of the circular bioeconomy and also zero-waste biomass valorization. Raw bio-oil cannot be directly utilised as a substitute to diesel fuel for CI engine application due to several inherent barriers. Although bio-oil diesel emulsion provides several benefits in terms of inherent oxygen in bio-oil, reduction in smoke and PM emissions; several challenges including extended ignition delay, lower BTE and greater corrosiveness and unknown effects on NOx levels limits the bio-oil diesel emulsion's prospective for a mass scale implementation. The influences of bio-oil emulsion on NOx levels primarily depend on many parameters such as bio-oil properties, diesel to bio-oil ratios, emulsifier concentration and engine operating conditions. A comprehensive review is presented, covering the combustion characteristics, engine performance and emission features of CI engines running on agro-residue bio-oil emulsions. Benefits and limitations of this emerging fuel are highlighted and research priorities identified.

Keywords: Biomass, bio-oil, CI engine, emulsion, pyrolysis

1. Introduction
Rising global energy demand, coupled with fossil fuel depletion concerns and tightening emission regulations, has intensified the search for cleaner alternatives to conventional diesel [1]. Compression ignition (CI) engines, widely used in transportation and agriculture, are major contributors to NOx and particulate matter (PM) emissions, making this transition particularly urgent [2]. Among emerging alternatives, bio-oil produced via fast pyrolysis of agro-residues such as rice husk, cotton stalk, and bagasse has gained attention as a renewable, non-food-competitive liquid fuel with potential for partial diesel substitution [3, 4]. However, its high viscosity, low heating value, poor stability, and limited miscibility with diesel preclude direct use in CI engines [3, 5]. Emulsification has emerged as a practical and cost-effective upgrading strategy, wherein bio-oil is blended with diesel using surfactants to improve viscosity, spray characteristics, and combustion behavior [6, 7]. The inherent oxygen content of bio-oil further offers potential reductions in smoke and PM emissions, though challenges related to ignition delay, reduced energy content, corrosion, and long-term durability remain [8, 9]. Given the inconsistent findings reported across the literature, particularly regarding NOx trends, this review critically examines the combustion performance and emission characteristics of agro-residue-based bio-oil emulsions in CI engines, while identifying key research gaps for large-scale application.

2. Biomass and Its Conversion
Biomass is any organic material that comes from plants or animals and serves as a source of energy. That includes things like wood, crop residues, animal manure, food waste, and even

algae. What makes biomass useful is that it stores energy from the sun through photosynthesis, and can release that energy again through processes like burning, fermentation, or conversion into fuels [10].

Biomass conversion includes a direct combustion, thermochemical and biochemical processes through which organic matter is transformed into energy carriers, including heat, electricity, and liquid or gaseous fuels [11]. The selection of an appropriate conversion pathway is governed by the type and composition of the feedstock, the desired end-product, and the intended application.

2.1 Direct combustion: Represents the simplest and most widely practiced conversion route, where in biomass is burned in the presence of excess air to release thermal energy for heating, cooking, and steam-based power generation. Despite its simplicity, direct combustion is associated with relatively low energy conversion efficiency and considerable particulate emissions [4].

2.2 Thermochemical conversion

Encompasses processes driven by the application of heat under controlled atmospheric conditions. Gasification involves the partial oxidation of biomass at elevated temperatures (700-1200°C), yielding a combustible gas mixture commonly referred to as syngas primarily composed of CO, H_2, and CH_4 [12]. Pyrolysis, conversely, involves thermal decomposition of biomass in the complete absence of oxygen at temperatures of 300-700°C, simultaneously yielding three co-products: bio-oil, biochar, and non-condensable syngas, with product distribution governed by temperature, heating rate, and vapor residence time [5, 13].

2.3 Biochemical conversion: Exploits microbial metabolic activity to extract energy from biomass. Anaerobic digestion decomposes organic matter in oxygen-free environments, producing biogas predominantly composed of methane (CH_4, 50-70%) and carbon dioxide (CO2, 15-20%) [14]. Fermentation utilizes microorganisms to convert fermentable sugars derived from lignocellulosic biomass into bioethanol, a widely adopted liquid biofuel for transportation applications [15].

3. Production of Bio-oil

Bio-oil is a dark brown, free-flowing liquid produced primarily through pyrolysis of lignocellulosic biomass at temperatures between 250-800°C under an inert atmosphere with rapid heating rates and short vapor residence times, typically containing 15-30 wt.% water and 35-40 wt.% oxygen. These characteristics result in a low heating value (15-19 MJ/kg), high acidity (pH 2-3), elevated viscosity, and poor thermal stability, making substitution for diesel fuel challenging with further upgrading or blending.

Bio-oil can be produced from different thermochemical conversion techniques, which are describe below:

Table 1: Thermochemical conversion of biomass

Process	Operating Conditions	Feedstock Suitability	Main Products	Key Features / Advantages	Reference
Pyrolysis	350-650 °C under reduced/limited oxygen	Dry biomass (wood, crop residues)	Bio-oil, syngas, biochar	Fast pyrolysis maximizes liquid yield, slow pyrolysis is char-oriented	[16]
Hydrothermal Liquefaction (HTL)	250-350 °C, 10-25 MPa in water	Wet biomass (sewage sludge, algae)	Bio-oil + aqueous phase	No pre-drying needed, handles high moisture feedstocks effectively	[17]
Gasification	Around 800 °C	Versatile biomass feedstocks	Syngas → liquid fuels/bio-oil via Fischer-Tropsch	Produces cleaner syngas, suitable for large-scale fuel synthesis	[18]
Improved / Catalytic Processes	Catalytic pyrolysis or post-upgrading, catalyst dependent	Various biomass types	Higher-quality bio-oil with reduced oxygen	Enhanced fuel stability and direct-use potential in transport fuels	[19]

3.1 Chemical and Physical Properties of Bio-oil

Bio-oil, also referred to as pyrolysis oil or bio-crude, produced through the rapid thermal decomposition of lignocellulosic biomass. Its chemical and physical properties differ substantially from those of conventional petroleum-derived diesel, presenting both unique opportunities and considerable challenges for direct application in CI engines [20].

3.1.1 Physical Properties

The physical properties of bio-oil differ considerably from those of conventional diesel fuel, as summarized in Table 2.

Table 2: Comparative properties of bio-oil and conventional diesel fuel

Property	Bio-oil	Diesel Fuel	Reference
Heating Value (MJ/kg)	15-19	42-45	[3, 5]
Water Content (wt.%)	15-30	~0.05	[9]
Oxygen Content (wt.%)	35-40	~0	[9]
Density (kg/m³)	1100-1300	820-845	[12]
Kinematic Viscosity (cSt, 40°C)	25-1000	2-4	[21]
pH	2-3	~6.5	[21, 22]
Flash Point (°C)	40-110	60-80	[22]
Carbon Content (wt.%)	54-58	86-87	[9]

3.1.2 Chemical Composition

Chemically, bio-oil is a complex multi-component mixture comprising several hundred organic compounds, including organic acids, aldehydes, ketones, alcohols, esters, furans, phenols, guaiacols, sugars, and water-soluble oligomers derived from cellulose, hemicellulose, and lignin decomposition [4, 13]. The oxygen content of bio-oil typically ranges between 35-40 wt.%, distributed across numerous oxygenated functional groups, which fundamentally distinguishes it from hydrocarbon-based petroleum fuels [11].

3.2 Methods of Bio-oil Upgrading

There are many different methods for upgrading bio-oil to use in engine, some of them are shows in figure 1:

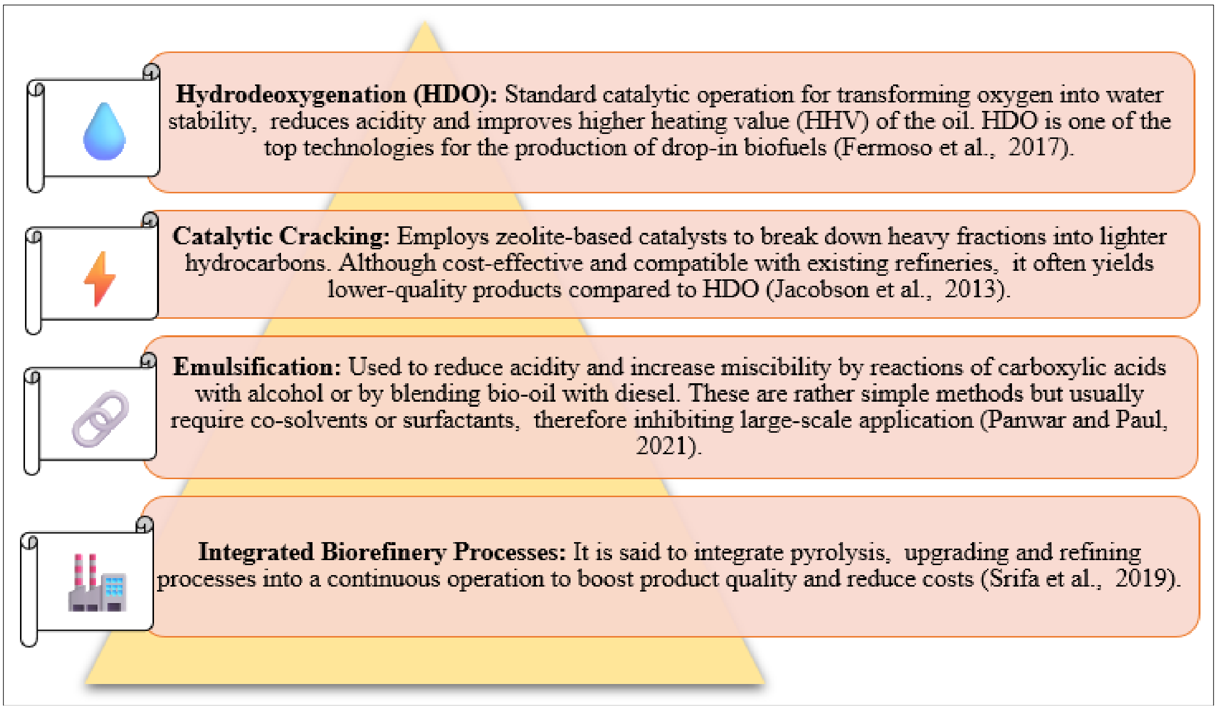

Fig 1: Methods of bio-oil upgrading [23]

4. Emulsification of Bio-oil with Diesel

Emulsification has emerged as one of the most practically viable and technically straightforward strategies for utilizing bio-oil in existing CI engines without requiring extensive fuel system modifications or costly upgrading infrastructure [3, 24]. An emulsion fuel is defined as a thermodynamically metastable, heterogeneous system in which two immiscible liquids are intimately dispersed as fine droplets within one another, stabilized through the action of surface-active agents known as emulsifiers [25].

4.1 Fundamentals of Emulsification

Bio-oil and diesel are inherently immiscible due to the highly polar, oxygenated nature of bio-oil and the non-polar hydrocarbon character of diesel fuel. Direct mechanical mixing of these two phases results in rapid phase separation, rendering the blend unsuitable for fuel applications [13]. Emulsification overcomes this thermodynamic incompatibility by employing surfactants that reduce interfacial tension at the bio-oil-diesel interface, enabling the formation of either oil-in-water (O/W) or water-in-oil (W/O) type emulsions [8, 25]. For CI engine applications, water-in-oil (W/O) emulsions, where water droplets are dispersed within a continuous diesel or diesel-bio-oil phase, are generally preferred because they preserve combustion characteristics closer to conventional diesel fuel [24, 26].

4.2 Role of Emulsifiers and Surfactants

Emulsifiers are indispensable components of stable bio-oil-diesel emulsion systems. Commonly employed surfactants include Span 80 (sorbitan monooleate), Tween 80 (polysorbate 80), and their binary combinations, which have been widely reported to yield stable emulsions at concentrations of 1-5 vol.% [8, 9, 25]. Excessive surfactant concentrations, however, have been associated with elevated NOx emissions and increased fuel costs, necessitating careful optimization. Biosurfactants derived from microbial or plant sources have also attracted growing interest as environmentally benign alternatives to synthetic surfactants, though their large-scale application remains at an early investigative stage [27].

4.3 Emulsion Stability and Storage

Long-term emulsion stability remains one of the principal technical challenges associated with bio-oil-diesel emulsion fuels. Phase separation, creaming, coalescence, and Ostwald ripening are the primary destabilization mechanisms that progressively degrade emulsion quality during storage [20, 28]. Stability is quantitatively assessed through measurements of droplet size distribution, zeta potential, viscosity evolution, and visual phase separation over defined storage periods [29]. Emulsions with a zeta potential exceeding ±30 mV are generally regarded as electrostatically stable systems. Studies have reported that optimally formulated bio-oil-diesel emulsions with 5-20 vol.% bio-oil content and appropriate surfactant combinations can maintain acceptable stability for periods ranging from several days to weeks under ambient storage conditions [30, 31].

5. Combustion, Performance and Emission Characteristics of Bio-oil Emulsions in CI Engines

The evaluation of combustion behavior, engine performance, and exhaust emission profiles constitutes the most critical dimension of assessing bio-oil emulsion fuels for practical CI engine applications [3, 5]. A thorough understanding of these interconnected characteristics is essential for identifying optimal blending strategies, operating conditions, and emission mitigation measures necessary for large-scale deployment [32]. Extensive experimental investigations conducted over the past two decades have collectively established a comprehensive knowledge base regarding the influence of bio-oil emulsification on CI engine operation, though considerable variability in reported outcomes persists across the literature owing to differences in feedstock origin, pyrolysis conditions, engine specifications, and test methodologies [12, 24].

Engine analysis for efficiency revealed that diesel-emulsified bio-oil was feasible to burn in diesel engines at acceptable efficiency. However, combustion was variable depending upon bio-oil molecular structure, with the requirement of oxygenated components for favoured micro-explosions that increased atomization but sometimes contributed to NOx formation augmentation [33]. More recently, bio-oil emulsion with vacuum gas oil and crude oils has also been included in studies, for potential application in refineries. The stabilized emulsion products with novel sets of surfactants showed extended stability and reduced corrosiveness, of crucial significance for application use [34, 35].

5.1 Combustion Characteristics

5.1.1 Ignition Delay

Ignition delay (ID) is defined as the crank angle interval between the start of fuel injection and the onset of combustion, encompassing both physical atomization and chemical pre-flame reaction processes [36, 37]. Bio-oil emulsion fuels consistently exhibit longer ignition delays compared to neat diesel, primarily attributable to their lower cetane number, higher water content, elevated viscosity, and reduced volatility, all of which collectively impede fuel-air mixture preparation and retard the initiation of auto-ignition chemistry [4, 13, 38]. Increasing bio-oil substitution ratios progressively extends the ignition delay period, as dilution of diesel with oxygenated bio-oil compounds reduces the overall reactivity of the fuel blend [9, 26]. Chiaramonti *et al.* 2003 reported that emulsions containing 10-25 vol.% bio-oil exhibited ignition delays 2-4 crank angle degrees (CAD) longer than neat diesel under equivalent operating conditions [8]. Similarly, Ikura *et al.* observed that increasing bio-oil content beyond 20 vol.% resulted in a disproportionate extension of ignition delay, attributed to the combined effects of reduced fuel reactivity and impaired spray atomization [24] [39]. The presence of water in the emulsion further absorbs latent heat during vaporization, lowering the local charge temperature and consequently extending the physical component of ignition delay [40, 41]. Several studies have proposed the incorporation of ignition-improving additives such as diethyl ether (DEE) and 2-ethylhexyl nitrate (EHN) as practical countermeasures for managing ignition delay in bio-oil emulsion systems [29, 42].

5.1.2 Cylinder Pressure and Peak Pressure

In-cylinder pressure development is a direct indicator of combustion intensity and thermodynamic work output in CI engines [37]. Studies consistently report that bio-oil emulsion fuels produce lower peak cylinder pressures compared to neat diesel, with the magnitude of reduction increasing proportionally with bio-oil blending ratio [4, 13, 39]. The lower heating value and extended ignition delay of bio-oil emulsions delay the pressure rise, shifting peak pressure toward later crank angle positions and reducing the rate of pressure rise (ROPR) [13, 40]. Across various studies, peak cylinder pressure reductions of 3-12% have been reported for bio-oil emulsions containing 10-30 vol.% bio-oil relative to baseline diesel operation [8, 9, 27]. Jayakishan *et al.*, 2024 observed that emulsified wood-derived bio-oil at 15 vol.% blending ratio produced peak pressures 6.5% lower than neat diesel at full load, attributing this to retarded combustion phasing and reduced energy density [43]. These reductions, while indicative of diminished combustion intensity, are also associated with lower thermal and mechanical stress on engine components, which may confer secondary durability benefits [26, 44].

5.1.3 Combustion Duration and Micro-explosion Phenomenon

Bio-oil emulsion fuels generally exhibit prolonged combustion durations compared to diesel, attributed to the combined effects of extended ignition delay, lower fuel reactivity, and the presence of water, which slows flame propagation kinetics [45-47]. The diffusion combustion phase is particularly extended in bio-oil emulsion systems, as the heterogeneous droplet composition and variable volatility of individual bio-oil constituents result in staggered vaporization and combustion events [48, 49]. The micro-explosion phenomenon in which trapped water droplets superheat and explosively vaporize within bio-oil droplets during combustion has been identified as a significant secondary atomization mechanism that enhances fuel-air mixing and partially compensates for the sluggish combustion kinetics of bio-oil emulsions [50-52]. Micro-explosions substantially improved droplet breakup in emulsified bio-oil systems, reducing mean droplet diameters by 30-50% compared to non-emulsified bio-oil sprays. This phenomenon is strongly influenced by the size of dispersed water droplets, bio-oil viscosity, and heating rate, and represents one of the most thermodynamically advantageous characteristics of emulsion fuel combustion [8, 13, 53].

5.2 Engine Performance Characteristics

5.2.1 Brake Thermal Efficiency

Brake thermal efficiency (BTE), which measures the fraction of fuel chemical energy converted into useful mechanical work at the crankshaft, is the primary indicator of overall engine performance [36]. Bio-oil emulsion fuels consistently exhibit lower BTE than neat diesel, with reductions of 2-8% depending on substitution level, load, and speed [4, 8, 15], primarily due to the lower calorific value, extended ignition delay, retarded combustion phasing, and energy losses from in-cylinder water vaporization and around 4.5% BTE reduction for a 20 vol.% blend under medium-to-high load conditions. These losses are most pronounced at low loads, where heat losses disproportionately dominate, but diminish at high loads as improved atomization and elevated in-cylinder temperatures partially compensate for inferior fuel properties [26, 27, 54]. Optimizing injection timing and pressure can recover up to 60% of the BTE deficit, while combustion-enhancing additives such as diethyl ether or cetane improvers further mitigate losses by reducing ignition delay and advancing combustion phasing [29, 42, 55].

5.2.2 Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) represents the mass of fuel consumed per unit of brake power output and is inversely related to BTE. Bio-oil emulsion fuels invariably exhibit higher BSFC compared to diesel, primarily due to their lower volumetric energy density necessitating greater fuel mass injection to maintain equivalent power output. BSFC increases of 5-20% have been reported across various studies for bio-oil blending ratios of 10-30 vol.%, with higher bio-oil fractions consistently yielding greater fuel consumption penalties [8, 27, 48]. BSFC increases of 8.3% and 14.7% for 10 and 20 vol.% bio-oil emulsion blends respectively at full load. similarly progressive BSFC escalation with increasing bio-oil content, attributing the trend primarily to the reduced lower heating value and increased ignition delay of the emulsion blends [56, 57]. Despite the higher BSFC, the renewable nature of bio-oil feedstocks offsets the economic and environmental implications of increased fuel consumption from a lifecycle perspective [12, 32, 58].

5.2.3 Brake Power and Torque Output

Bio-oil emulsions generally produce marginally lower brake power and torque output compared to neat diesel at equivalent throttle and injection settings, consistent with their reduced heating value and combustion efficiency [9, 39, 48]. Power output reductions of 3-10% have been reported for emulsion blends containing 20-30 vol.% bio-oil [53, 59]. Brake power reductions of approximately 5-7% for wood-derived bio-oil emulsions, similar trends for rice husk bio-oil blends. These reductions are considered acceptable within the context of renewable fuel integration, particularly when optimized injection timing and pressure strategies are employed to recover performance losses [29, 45, 55].

5.3 Emission Characteristics

5.3.1 Nitrogen Oxide (NOx) Emissions

The effect of bio-oil emulsions on NOx emissions is multifaceted and subject to considerable variability, reflecting the complex and competing influences of fuel oxygen content, adiabatic flame temperature, ignition delay, and water content on thermal NOx formation kinetics [20, 50, 60]. The lower calorific value and heat-absorbing effect of water vaporization in bio-oil emulsions reduce peak combustion temperatures, thereby suppressing thermal NOx formation. Several studies have reported NOx reductions of 5-20% for bio-oil emulsion blends relative to neat diesel, attributing these reductions to the combined cooling effect of water vaporization and retarded combustion phasing [48, 57, 61]. Conversely, other investigations have reported marginal NOx increases, particularly at high engine loads, where the elevated oxygen content of bio-oil promotes more complete combustion and raises local flame temperatures and the NOx emission trend reversed from reduction to increase as engine load exceeded 75% of rated capacity, attributing this behavior to the dominance of the fuel oxygen contribution over the water-cooling effect at high temperatures. The net NOx outcome is therefore a strong function of the balance between competing mechanisms and is highly sensitive to engine operating conditions, blending ratio, emulsifier concentration, and bio-oil feedstock composition [29, 43, 62].

5.3.2 Smoke and Particulate Matter (PM) Emissions

Bio-oil emulsion fuels demonstrate a consistent and well-documented advantage over conventional diesel in terms of smoke opacity and particulate matter (PM) emissions, representing the most significant and reliable environmental benefit of bio-oil emulsification [4, 8]. The high intrinsic oxygen content of bio-oil typically 35-40 wt.% promotes more complete oxidation of carbonaceous species during the diffusion combustion phase, substantially suppressing soot nucleation and growth processes. Smoke opacity reductions of 15-40% have been widely reported for bio-oil emulsion blends relative to neat diesel, with greater reductions observed at higher bio-oil fractions [13, 24, 27, 63]. Murugan *et al*. 2008 reported smoke reductions of up to 35% for 20 vol.% rice husk bio-oil emulsions, while Hossain and Davies 2010 observed smoke opacity reductions of 22-28% for wood bio-oil blends across all load conditions[54, 63]. The micro-explosion mechanism characteristic of emulsion fuels further contributes to PM reduction by promoting secondary atomization and improving fuel-air mixing homogeneity, thereby reducing fuel-rich combustion zones responsible for soot formation [43, 46, 52]. The water content of bio-oil emulsions additionally promotes soot oxidation through steam-carbon reforming reactions, further contributing to lower PM emissions [40, 41, 64].

5.3.3 Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) emissions from CI engines result from incomplete combustion due to insufficient local oxygen availability, low combustion temperatures, or inadequate fuel-air mixing. Bio-oil emulsion fuels exhibit variable CO emission behavior depending on bio-oil content, engine load, and combustion temperature. At low to moderate engine loads, higher CO emissions are commonly reported for bio-oil emulsions compared to diesel, attributed to lower combustion temperatures, extended ignition delay, and the quenching effect of water vaporization that inhibits complete CO oxidation to CO_2 [13, 29, 40]. Amalina *et al*., 2023 reported CO emission increases of 12-22% at partial load conditions for 20 vol.% bio-oil emulsions, while Geo *et al*. 2011 observed similar trends across a range of blending ratios and engine speeds[27, 65]. At higher engine loads, the elevated oxygen content and improved atomization of bio-oil emulsions promote more complete combustion, often yielding CO emissions comparable to or marginally lower than neat diesel [26, 54, 63].

5.3.4 Carbon Dioxide (CO_2) and Greenhouse Gas Emissions

Bio-oil emulsion fuels generally yield lower net CO_2 emissions on an energy-output basis compared to fossil diesel within a lifecycle assessment (LCA) framework, a consequence of the renewable biogenic carbon cycle governing agricultural residue-derived feedstocks [11, 32]. The biogenic CO_2 released during combustion of bio-oil emulsions is considered carbon-neutral, as it is balanced by the CO_2 sequestered during biomass growth [53, 58]. Nevertheless, on a per-kilogram-of-fuel basis, higher BSFC associated with bio-oil emulsions results in marginally elevated CO_2 mass flow rates per unit time, highlighting the importance of system-level emission accounting over instantaneous tailpipe measurements [26, 27, 56].

6. Key Technical Challenges

A major challenge for the practical utilization of bio-oil emulsion fuels is their poor compatibility with conventional fuels and CI engine components. Bio-oil is highly acidic (pH 2-3), leading to corrosion of injectors and fuel system parts [66]. Its high viscosity results in poor atomization, larger droplets, and reduced combustion efficiency, while long-term use promotes deposits and component wear. Additionally, bio-oil-diesel emulsions are thermodynamically unstable and prone to phase separation, with aging further increasing viscosity through polymerization reactions. Lower cetane number, longer ignition delay, and reduced calorific value also reduce stable combustion, particularly under low-load and cold-start conditions [67, 68].

Despite these limitations, bio-oil offers significant advantages as a renewable fuel. It can be produced from abundant biomass waste, supports waste valorization, and reduces dependence on fossil fuels. Its inherent oxygen content can improve combustion and lower particulate emissions under optimized conditions. With appropriate upgrading and engine modifications, bio-oil remains a promising candidate for sustainable CI engine applications [69, 70].

7. Future Research Directions

Several high-priority research directions are essential for accelerating the practical deployment of bio-oil emulsion fuels. First, the development of standardized fuel quality specifications covering acidity, viscosity, water content, heating value, and stability is critical for commercial adoption, as such standards are currently lacking [69, 71]. Second, long-term engine durability studies focusing on injector wear, piston degradation, and fuel system corrosion are needed, since most existing work is limited to short-term trials. Third, coupling bio-oil emulsions with advanced low-temperature combustion (LTC) strategies such as Homogeneous Charge Compression Ignition (HCCI) and Reactivity-Controlled Compression Ignition (RCCI) offers strong potential to address ignition and emission challenges but remains largely unexplored.

In addition, machine learning and artificial intelligence can be used to predict fuel properties and optimize combustion parameters, reducing experimental effort and cost. Finally, region-specific lifecycle assessment (LCA) and techno-economic analysis (TEA) are essential to evaluate sustainability and guide effective bioenergy policy, particularly for agro-residue-based feedstocks [72, 73].

8. Conclusion

Agricultural bio-oil emulsions are promising renewable fuels for CI engines and support a circular bioeconomy through biochar and syngas co-products. However, high acidity, viscosity, low heating value, and poor stability limit direct use. Emulsions (10-30%) improve atomization via micro explosions, reducing smoke and particulates but slightly lowering efficiency. Combustion shows longer ignition delay and lower peak pressure. Challenges include corrosion, cold starts, instability, and lack of standards, while advances in upgrading, additives, and low-temperature combustion strategies are needed for wider adoption.

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