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Review Article

Optimizing IC engine efficiency: A comprehensive review on biodiesel, nanofluid, and the role of artificial intelligence and machine learning

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ABSTRACT

Transportation and power generation have historically relied upon Internal Combustion Engines (ICEs). However, because of environmental impact and inefficiency, considerable research has been devoted to improving their performance. Alternative fuels are necessary because of environmental concerns and the depletion of non-renewable fuel stocks. Biodiesel has the potential to reduce emissions and improve sustainability when compared to diesel fuel. Several researchers have examined using nanofluids to increase biodiesel performance in internal combustion engines. Due to their thermal and physical properties, nanoparticles in a host fluid improve engine combustion and efficiency. This comprehensive review examines three key areas for improving ICE efficiency: biodiesel as an alternative fuel, application of nanofluids, and artificial intelligence (AI)/machine learning (ML) integration. The integration of AI/ML in nanoparticle-infused biodiesel offers exciting possibilities for optimizing production processes, enhancing fuel properties, and improving engine performance. This article first discusses, the benefits of biodiesel concerning the environment and various difficulties associated with its usage. The review then explores the effects and characteristics of nanofluids in IC engines, aiming to know their impact on engine emissions and performance. After that, this review discusses the utilization of AI/ML techniques in enhancing the biodiesel-nanofluid combustion process. This article sheds light on the ongoing efforts to make ICE technology more environmentally friendly and energy-efficient by examining current research and emerging patterns in these fields. Finally, the review presents the challenges and future perspectives of the field, paving the way for future research and improvement.

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1. Introduction

The burgeoning demand for alternative fuels stems from the urgent need to address environmental concerns, reduce reliance on fossil fuels, and foster sustainability within the energy sector [1]. Conventional fuels like gasoline and diesel demonstrably contribute to air quality deterioration and greenhouse gas emissions, exacerbating climate change and posing significant public health risks [2]. This has led to a global consensus on transitioning towards cleaner and more sustainable energy sources. Alternative fuels offer numerous advantages over their conventional counterparts [3]. They are frequently produced from renewable resources such as plant biomass, algae, and organic waste, making them inherently more environmentally friendly [4]. These fuel sources are capable of reducing carbon dioxide emissions, particulate matter, and other harmful pollutants, thereby mitigating their negative impacts on air quality and human health. Additionally, the finite nature of fossil fuel reserves and the geopolitical complexities surrounding their extraction and distribution have served as powerful motivators for exploring alternative energy options [5]. Diversifying their energy mix presents an opportunity for nations to enhance energy security and reduce dependence on fossil fuel importers. Regulatory pressure to reduce emissions has fueled the demand for alternative fuels. Numerous countries have implemented renewable energy targets and tightened emission regulations, creating a supportive environment for the development and adoption of these alternatives. Technological advancements have further bolstered the viability and cost-competitiveness of alternative fuels. Research & Development efforts have focused on streamlining production processes, enhancing yields, and optimizing fuel performance. Breakthroughs in fuel cell technology, biofuel production techniques, and energy storage systems have played a key role in improving the practicality and economic sustainability of these fuels [6]. However, as Fig. 1 illustrates, greenhouse gas (GHG) emissions continued to rise until 2021, acting as the primary driver of global temperature increase. GHGs remain the leading contributor to global warming, and their reduction is crucial to addressing this critical challenge. Fig. 2 further details regional GHG emissions [7].

Most of the world's transportation energy is derived from two fuels: motor gasoline (including ethanol mixes) and diesel (including biodiesel blends) [8]. The combined use of these two fuels accounted for 75 % of the energy used in vehicles [9]. The primary purpose of gasoline is to power light-duty vehicles for transportation of people. The most common application for diesel fuel is in the car of products, particularly by heavy-duty trucks. The energy used for transportation comes mostly from jet fuel (12 %) and residual fuel oil (9 %). Non-petroleum fuels account for a modest percentage of the world's energy mix, with natural gas and electricity accounting for approximately 4 % of the world's total transportation energy consumption. Petroleum products make up most of the world's transportation energy consumption by a significant margin [10]. Fig. 3 displays the energy consumption of transportation modes worldwide and selected countries and regions in quadrillion Btu and percentages.

Worldwide passenger travel demand, across all modes including light-duty vehicles, buses, two/three-wheelers, trains, and aircraft, is projected to continue its historical growth trajectory until 2050. Global travel is expected to nearly double by the end of 2023, reaching 80 trillion passenger miles, a full recovery to its 2019 peak. This surge is primarily driven by the rise in light-duty vehicle trips in non-OECD countries. Between 2020 and 2050, the annual average population growth rate in non-OECD countries was three times higher than in OECD countries, resulting in a widening gap in travel demand per capita growth, as illustrated in Fig. 4 [11].

Biodiesel, a clean-burning fuel derived from plants, animal fats, and used cooking oil, is a promising alternative to traditional diesel [12]. Produced through a chemical process known as transesterification, biodiesel offers several environmental benefits. It is biodegradable, reduces greenhouse gas emissions, and improves air quality compared to petroleum diesel. Sourced from renewable resources like soybean oil and used cooking oil, biodiesel offers a sustainable alternative to finite fossil fuels. It also enhances energy security by reducing reliance on imported oil and stimulates rural economies through feedstock cultivation. Another advantage is its compatibility with existing engines and infrastructure. Biodiesel can be used directly or blended with regular diesel without requiring significant modifications, making it readily usable across various sectors. Additionally, promising feedstocks like algae hold the potential for carbon neutrality, further reducing environmental impact. Biodiesel emissions are demonstrably lower than petroleum diesel, contributing to improved public health [13]. It is also compatible with most diesel vehicles, requiring only minor adjustments for optimal performance. This compatibility makes it a readily implementable solution for cleaner transportation and a more sustainable future.

The application of nanofluids, composed of minuscule particles dispersed within a base fluid, has witnessed a considerable surge in interest due to their anticipated ability to enhance the operational efficiency of internal combustion engines (ICEs) [14]. As depicted in Fig. 5 (a), carbon nanotubes are just one example of the diverse range of nanoparticles used, and Fig. 5(b) showcases the broad applications of nanofluids. These remarkable materials, with their unique thermal,

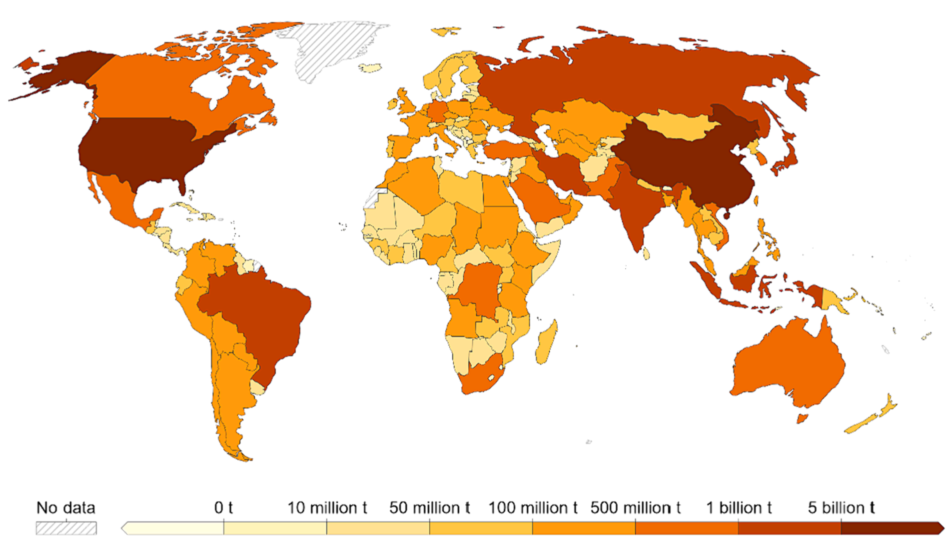

Fig. 1. Global GHG emissions up to year 2021 [7]

physical, and chemical properties, can significantly enhance engine performance. Nanofluids' exceptional thermal conductivity, thanks to the nanoparticles, leads to noticeably improved heat transfer [15]. This translates to more efficient cooling of cylinder walls, pistons, and cylinder heads, optimizing thermal management. In addition, nanoparticles reduce frictional resistance and enhance engine lubricity, leading to less energy wasted through friction. This not only increases engine efficiency but also reduces wear and tear, potentially extending its lifespan. Nanofluids also play a crucial role in reducing emissions. Their superior thermal conductivity and combustion properties promote more efficient fuel burning, leading to lower levels of harmful pollutants like NOx, PM, and unburned hydrocarbons [16]. The exceptional properties of nanofluids align seamlessly with the growing demands of stringent environmental regulations and stricter air quality standards. These remarkable materials offer further enhancements in combustion efficiency and emission reduction by improving fuel droplet atomization and vaporization. The increased interfacial area created by nanoparticles within fuel droplets accelerates fuel–air mixing, leading to cleaner and more efficient combustion. Additionally, nanofluids can form a protective layer on engine surfaces, bolstering wear and corrosion resistance [17]. This protective shield mitigates the detrimental effects of friction, heat, and chemical reactions, ultimately enhancing the durability and reliability of engine components. Overall, nanofluids present a promising avenue for simultaneously improving the efficiency, emissions, and lifespan of internal combustion engines. Their unique properties address several key challenges faced by conventional engines, paving the way for a cleaner and more sustainable future in the automotive industry.

The widespread adoption of Artificial Intelligence (AI) and Machine Learning (ML) has ignited a rapid transformation within the automotive industry. To clarify, AI encompasses the entire spectrum of intelligent machines that can mimic human cognitive functions like learning, reasoning, problem-solving, and decision-making [20]. AI employs various approaches like rule-based systems, expert systems, natural language processing, computer vision, and machine learning. ML is a specific technique within AI that focuses on algorithms that can learn from data without explicit programming. ML utilizes various algorithms like supervised learning, unsupervised learning, and reinforcement learning to learn from data and make predictions or decisions. The automotive industry is currently experiencing a substantial transformation driven by four prominent trends: autonomous driving, connectivity, electrification, and shared mobility (ACES) [21]. These trends are poised to reshape the market, causing disruptions to traditional models while introducing innovative technologies and business strategies. In the context of ACES, artificial intelligence (AI) plays a pivotal role across each trend. In autonomous driving, AI is indispensable for enabling real-time object recognition and decision-making, thereby making self-driving vehicles a reality. In terms of connectivity, AI optimizes pricing and operations for connected car services, enhances maintenance scheduling, and facilitates more efficient fleet management. Electrification benefits from AI through enhanced battery management, optimized charging infrastructure, and personalized charging experiences. Lastly, in shared mobility, AI's predictive capabilities contribute to matching supply and demand for services, resulting in efficient resource allocation. The integration of AI offers automotive companies several advantages. Firstly, it enables cost reduction by streamlining operations, optimizing resource allocation, and predicting maintenance needs, ultimately leading to financial savings. Secondly, AI improves overall operations by optimizing pricing, personalizing experiences, and enhancing fleet management, thereby increasing operational efficiency. Lastly, AI opens doors to new revenue streams by enabling innovative services, personalized offerings, and targeted advertising opportunities. Fig. 6 highlights the importance of AI in road safety. Many AI/ML has been applied in biodiesel and nanofluid research. These include Artificial Neural Network (ANN), Multi-Layer Perceptron Neural Network (MLPNN), Radial Basis Function Neural Network (RBFNN), Adaptive Neuro-Fuzzy Inference System (ANFIS), Extreme Learning Machine (ELM), Kernel Extreme Learning Machine (KELM), Support Vector Machine (SVM), Relevance Vector Machine (RVM), Bidirectional Recurrent Neural Network (BRNN), Additive Multi-Task Learning (AMT) and Genetic Algorithm (GA) [22–28].

Environmental concerns and the need to reduce fossil fuel dependence have fostered the demand for alternative fuels. Conventional fuels contribute to air pollution and greenhouse gas emissions, exacerbating climate change. Alternative fuels, often derived from renewable resources, offer advantages such as reduced carbon emissions and particulate matter. The limited nature of fossil fuel reserves and geopolitical complexities have further driven the exploration of alternative energy options. Regulatory pressure and technological advancements have bolstered the viability and cost-competitiveness of these fuels. Biodiesel and nanofluids represent promising alternative fuel options with distinct advantages.

While existing review articles explore ICEs efficiency, they often lack granularity regarding specific engine types. Future research should differentiate between petrol and diesel engines, and even delve into two-stroke versus four-stroke variations, to provide more nuanced insights. Similarly, for biodiesel, the impact of diverse source materials on engine performance and optimal blend ratios with conventional diesel warrants further investigation. Nanofluids, with their properties influenced by base fluid and nanoparticle types, necessitate further research, particularly regarding their direct impact on engine efficiency, encompassing heat transfer and viscosity. The potential integration of AI/ML systems

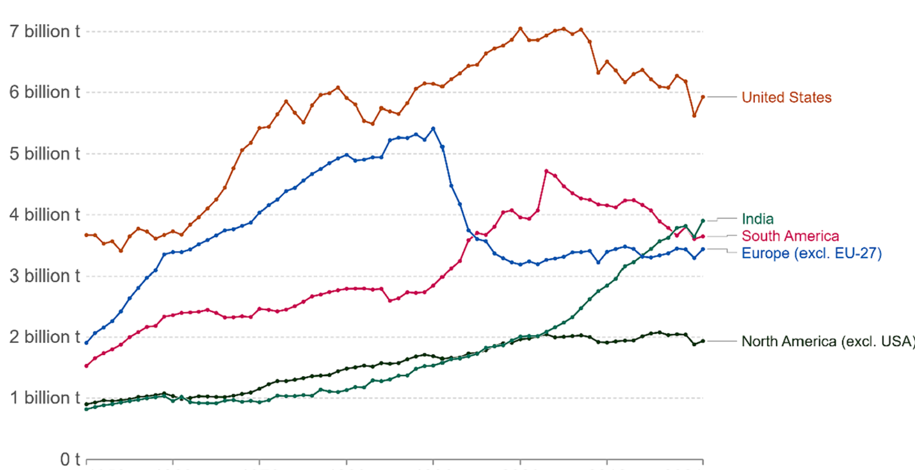

Fig. 2. Regional GHG emissions through the year 1950–2022 [7]

within ICE ecosystem presents a unique challenge due to inherent domain difficulties, such as real-time data processing and sensor calibration. Moreover, the long-term effects of employing biodiesel, nanofluids, and AI/ML require thorough analysis. While efficient engines contribute positively to the environment, a holistic perspective is crucial. The environmental impact of biodiesel production, nanofluid application, and the energy demands of AI/ML systems themselves should not be overlooked. Therefore, this article aims to bridge the gap between theoretical frameworks and real-world applications by demonstrating the tangible benefits of these technologies in practical scenarios.

2. Biodiesel as an alternative fuel

2.1. Production process of biodiesel

Biodiesel emerges as a promising and environmentally conscious alternative to conventional diesel fuel, garnering attention for its sustainability credentials [29]. This champion of renewable energy sources exhibits the remarkable ability to replace diesel in existing engines without necessitating modifications directly. Fig. 7 offers a concise visual representation of the key stages involved in its production process.

2.1.1. Feedstock selection

The journey to clean-burning biodiesel begins with a crucial choice: selecting the ideal feedstock. This raw material can be diverse, ranging from familiar vegetable oils like rapeseed and soybean to animal lipids like tallow and lard [30]. Feedstock selection mainly depends upon availability, cost, and environmental factors. The significance of availability depends on various factors like geographical location, climate conditions, and agricultural practices [2]. Finding feedstocks that can be obtained sustainably without threatening the environment or the food supply is crucial. Ippolito et al. [31] examine how feedstock, pyrolysis temperature, and type affect biochar production. Feedstock choice most affects biochar attributes, with wood-based biochars having higher specific surface area and cation exchange capacities. The information can help design biochars for crop growth and environmental challenges. Market dynamics and competing interests are the only variables affecting how much a good or service costs. The economic feasibility of biodiesel manufacturing hinges heavily on both feedstock pricing and accessibility. Environmental concerns encompass not just the production costs but also the impact on land use, water resources, and biodiversity [32]. Anwar [33] investigated the selection of the optimal biodiesel feedstocks using multiple criteria decision analysis (MCDA) procedures, considering economic, technical, environmental, and social factors. Notably, his analysis ranks coconut as the most favorable feedstock, with soybean faring the worst. Opting for feedstocks with minimal environmental footprints, such as waste oils or non-food crops, paves the way for sustainable biodiesel production. In essence, selecting the appropriate feedstock necessitates a comprehensive evaluation of availability, cost, and environmental impact. This critical step ensures the long-term sustainability and financial viability of biodiesel production.

Fig. 8 offers an overview of major biodiesel feedstock sources from 2016 to 2022, focusing on the world's fastest-growing economies [34,35]. Globally, over 350 oil-rich plant species boast potential for biodiesel production [36–38]. A key benefit of biodiesel lies in its versatility, enabling its manufacture from a diverse array of established feedstocks.

Across various generations of biodiesel production, the utilized feedstock landscape has demonstrably diversified. Table 1 provides a comprehensive overview of the diverse range of feedstocks employed in the manufacturing process, encompassing first to fourth generation biodiesels.

2.1.2. Pre-Treatment

Following feedstock selection, a meticulous pre-treatment process ensures the integrity and purity of the chosen material for subsequent processing [48]. This critical step involves a multi-stage purification to remove impurities and contaminants. Firstly, any solid particles and waste are filtered out, enhancing feedstock clarity and preventing potential blockages in production machinery [49]. Secondly, moisture extraction is vital. Excessive moisture can lead to detrimental emulsions, microbial growth, and catalyst deactivation, compromising biodiesel quality. Therefore, pre-treatment prioritizes moisture removal to maintain feedstock integrity. Additionally, pre-treatment addresses free fatty acids (FFAs) in the feedstock. FFAs can disrupt the transesterification reaction, the key chemical conversion to biodiesel [50]. Techniques like acid esterification or neutralization effectively reduce FFA content. Furthermore, pre-treatment can employ supplementary purification measures to remove undesirable compounds like gums, resins, or pigments, preparing the feedstock for optimal conversion to biodiesel [51]. While bifunctional solid catalysts offer combined transesterification and esterification, their sluggish reaction rates and high temperature demands limit their application [52]. Therefore, acid esterification pre-treatment prevails for reducing FFAs in biodiesel feedstocks [53,54], even enabling FFA-based biodiesel production. Glycerolysis also holds promise for FFA-rich feedstocks, as evidenced by studies [55,56]. Adepoju et al. [57] predicted rubber seed oil acidity better than the RSM model. Ofoefule et al. [58] observed that the Multi-Layer Perceptron Neural Network (MLPNN) topology predicted a decrease in African pear seed oil FFA. The MLPNN model was used by

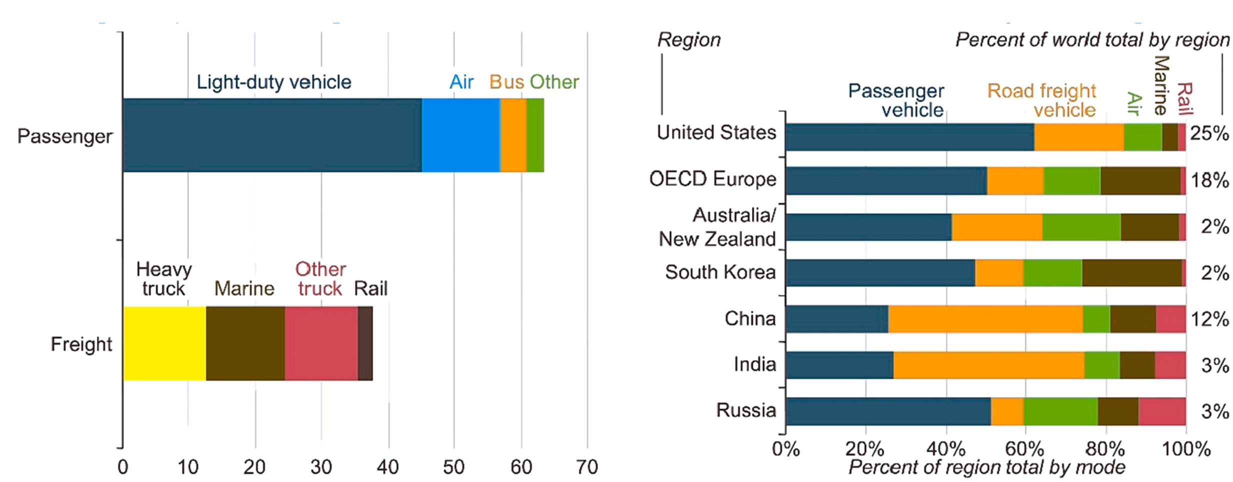

Fig. 3. World transportation and selected country and region transportation energy consumption by mode (quadrillion Btu and percent) [10].

Satyanarayana and Muraleedharan [54] to model rubber seed oil's ultimate acid value during esterification. Jena et al. [59] used the Genetic Algorithm (GA) paradigm and MLPNN architecture to optimize and model FFA levels during non-edible oil esterification. Silitonga et al. [60] successfully modeled and optimized *Cerbera manghas* oil esterification FFA reduction using MLPNN-Ant Colony Optimization (ACO). GA is a stochastic search strategy inspired by natural evolution [60]. Islam et al. [61] in accurately predicting and optimizing FFA-rich biodiesel feedstock glycerolysis by lowering final acid levels through their MLPNN-GA model. This meticulous pre-treatment step ultimately guarantees the quality and efficiency of the entire biodiesel production process.

2.1.3. Fuel conversion Techniques

The transesterification process is central to biodiesel production. During this stage, the chosen oil or fat undergoes a chemical reaction with methanol, facilitated by a catalyst like NaOH or KOH [62]. This reaction aims to convert the triglycerides within the oil or fat into esters, the primary constituents of biodiesel, while simultaneously generating glycerol as a by-product [63]. In essence, transesterification breaks down the ester bonds in triglycerides and forms new ones with alcohol. Converting crude tamarind oil into tamarind biodiesel and glycerol involves three sequential chemical reactions. First, triglycerides are converted into diglycerides. Subsequently, diglycerides are converted into monoglycerides. Finally, monoglycerides undergo a final transformation into glycerol.

Sagiroglu et al. [64] generated biodiesel from methanol and 1.85 % HCl. Safflower and soybean oils yielded 94.3 % and 94.2 % biodiesel at 100 °C in 1 h. In 3 h at 25 °C, yields were 84.7 % and 85.9 %. Higher temperatures improved safflower and soybean oil outputs by 11.3 % and 9.7 %, respectively. Preheating cultivates biodiesel. The catalyst enhances the esterification rate and facilitates the conversion of triglycerides to biodiesel. Wang et al. [65] developed a solid superacid catalyst, $S_2O_8^{2}-/ZrO_2$, for biodiesel generation from expired soybean oil utilizing a one-pot approach with ammonium persulfate In 4 h at 100 °C with three wt% catalyst and 20:1 methanol to oil, 100 % biodiesel was produced. The stable catalyst did not leach sulfur. The transesterification process is commonly carried out with careful regulation of various parameters, such as temperature, pressure, and reaction duration, to maximize the efficiency of converting the raw material into biodiesel. Once the transesterification process is complete, the mixture is extracted, and the biodiesel is purified to meet quality standards for use as fuel [66]. Biodiesel production from transesterification can be accomplished by either the supercritical methanol or catalytic transesterification processes [67]. Table 2 shows the transesterification conditions for various feedstocks.

2.1.4. Separation, Purification, and refining

Following biodiesel production, glycerol is separated through sedimentation (settling) or centrifugation techniques [80]. Biodiesel undergoes further purification processes, such as washing, to remove residual catalysts, soaps, and other contaminants. Water or specific washing solutions effectively extract water-soluble impurities and unreacted components. Subsequently, the biodiesel is desiccated to eliminate any residual moisture that could compromise its quality and performance. Drying techniques employ gravity settling, specialized dryers, or filters [81]. These rigorous purification and isolation steps ensure that the final biodiesel meets stringent regulatory standards. Fig. 9 highlights the traditional purification steps for biodiesel production.

For water conservation in crude biodiesel production, dry washing is an option. Sorbents and acid resins purify biodiesel, minimizing water contamination and production time. There are many ways to purify crude glycerol. According to the quantity and composition of glycerol, purification methods may vary. The variable design of crude glycerol makes universal purification difficult. Saponification, acidification, phase separation, neutralization, and solvent-based anti-solvent treatment are standard physio-chemical therapies [82,83]. Advanced refining procedures include ion exchange [84], vacuum distillation [85], adsorption [86], membrane separation [87], membrane distillation [88] and electrodialysis [89]. Fig. 9 shows four refining steps conventionally required to purify glycerol [90].

Further refining operations like degumming and neutralization can improve biodiesel quality. Biodiesel (FAME) generated by methanolysis of soybean and waste cooking oils over a heterogeneous calcium-based catalyst was dry washed by Catarino et al. [91] using Evonik Sipernat 22 silica sorbent. ATR-FTIR spectra of post-purification sorbents showed that silica removed unreacted oil species, Ca soap, glycerin, and leached calcium from biodiesel, contrary to earlier literature. The sorption test at 45 ℃ for 60 min yielded the best purity for both feedstocks. The process of degumming serves to eliminate impurities and gums, whereas neutralization is employed to decrease acidity levels. Arenas et al. [92] offered bio-adsorbents such as sawdust, coconut fiber, nutshell, rice husk, and water hyacinth fiber to purify biodiesel from waste cooking oil. Sawdust purification reduced the acid number by 31.3 % compared to unpurified biodiesel. Sawdust reduced better than Amberlite BD10DRY, which enhanced acidity. Sawdust also reduced free glycerin 54.8 % better than Amberlite BD10DRY. These processes aim to refine the gasoline so that it is more stable, free of contaminants, and up to par with established norms. The enhancement of biodiesel's overall quality and transformation into a reliable and high-performance renewable fuel option is achieved by implementing appropriate drying methods and refining techniques.

2.1.5. Storage and distribution

Following production and refinement, biodiesel undergoes careful storage in suitable containers to safeguard its quality. Proper storage practices that minimize exposure to air and moisture are crucial to

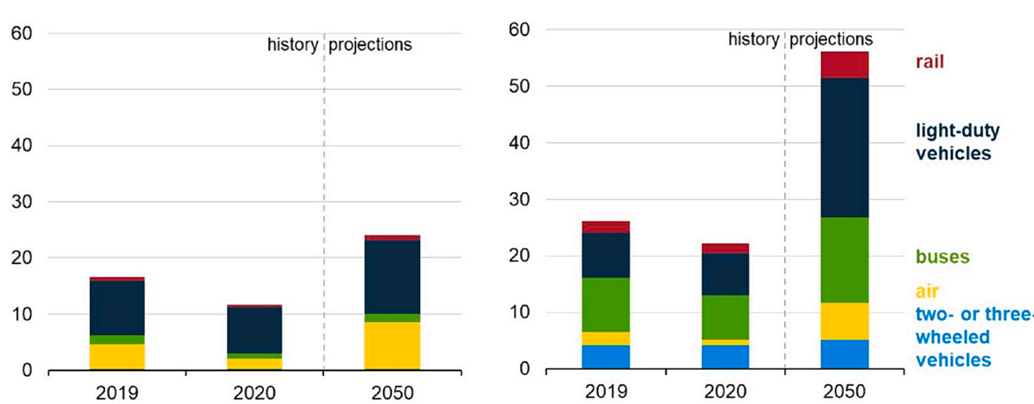

Fig. 4. Demand for passenger travel by mode for OECD and non-OECD countries (trillions of passenger miles) [11].

prevent degradation [93]. Biodiesel's blend-ability with petroleum diesel in varying proportions facilitates its seamless integration into existing infrastructure [94]. However, Prince et al. [95] caution that biodiesel blends' FAME content is more prone to breakdown, potentially contaminating fuel storage systems. This, along with fuel pollution and degradation, necessitates addressing additional concerns. Standard blends include B5, B20, and B100, and the blending process enhances compatibility and utilization in diesel engines [96]. Biodiesel distribution leverages a distributed system for delivery to fuel stations and industrial sites [97]. As demand and regulatory support grow, the distribution network will expand to accommodate wider user access [98].

Lee et al. [99] and Aktas et al. [100], biodiesel microbes increase corrosion rates. A 2016 US EPA research found moderate to severe corrosion in 83 % of storage tanks. This shows biodiesel degradation may affect the durability of fuel infrastructure. The maintenance of biodiesel quality, stability, and a dependable supply necessitates the implementation of efficient storage and distribution processes. While laboratory studies suggest that biodiesel blends biodegrade due to microbial metabolism, the connection between non-marine microbial communities and higher corrosion rates in real-world scenarios remains unclear [101]. Stamps et al. [102] investigated B20 storage tanks and found gasoline fouling and corrosion-associated microorganisms in two locations. This first-of-its-kind in-situ study linked Trichocomaceae abundance to apparent fouling and pitting corrosion. Notably, the fuel acid number from SE 3 increased from 0.17 to 1.51 mg KOH/g B20, exceeding the ASTM standard level of 0.3 mg KOH/g B20 after 9 months. SEM images of witness coupons from both locations revealed similar biofilms (Fig. 10 A) with predominantly fungal structures (Fig. 10 C). These coupons' pits corresponded to biofilm-covered locations before cleaning (Fig. 10 B, D). The increased acidity led to higher corrosion rates and deeper pit marks in SE tank 3 compared to others. This increased acidity caused higher corrosion rates and deeper pit marks in SE tank 3 than in other tanks. This makes it easier for it to be integrated into the existing diesel fuel infrastructure, which in turn helps enable its use in various applications [103]. The findings highlight the importance of efficient storage and distribution processes in maintaining biodiesel quality, stability, and reliable supply. While blending facilitates integration into existing diesel infrastructure, promoting wider adoption necessitates close attention to potential challenges like

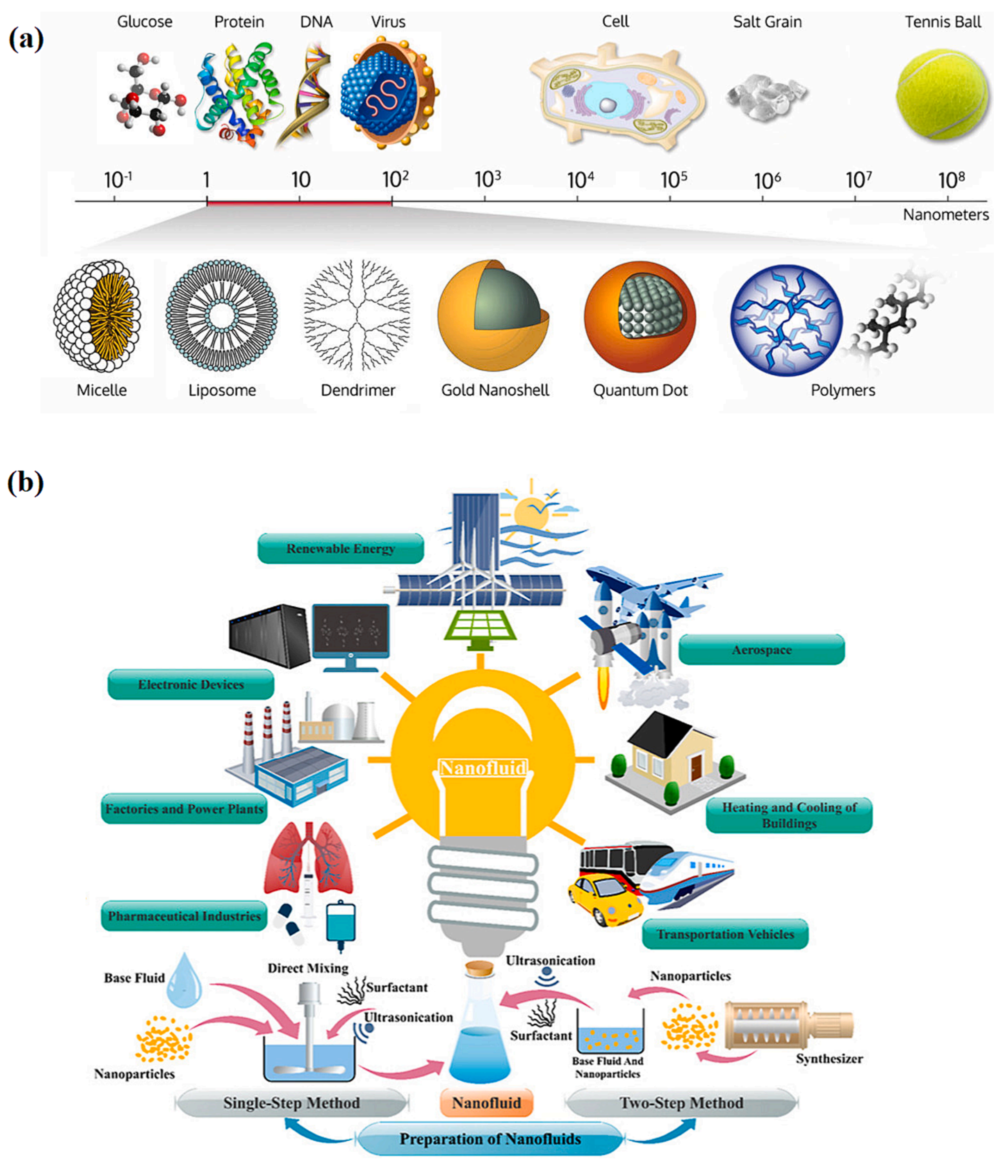

Fig. 5. (a) Scale of carbon nanotubes to various materials [18], and (b) diverse applications of nanofluids [19] (Adapted with permission from Elsevier BV with License No: 5723471386257).

Fig. 6. Road safety enhancement through AI.

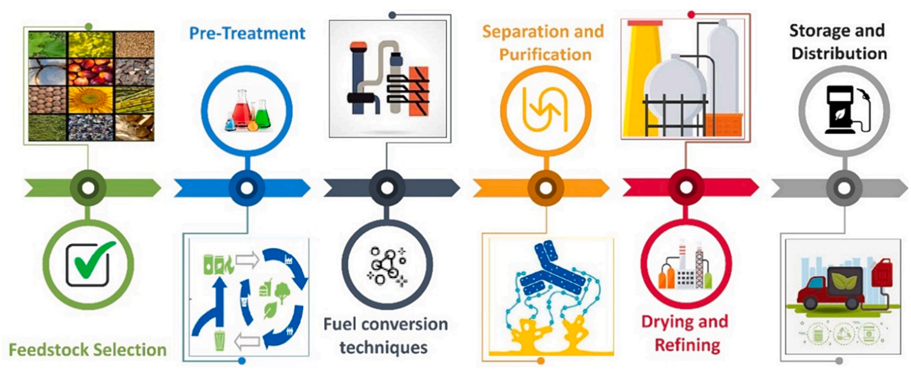

Fig. 7. The functional key stages of biodiesel production.

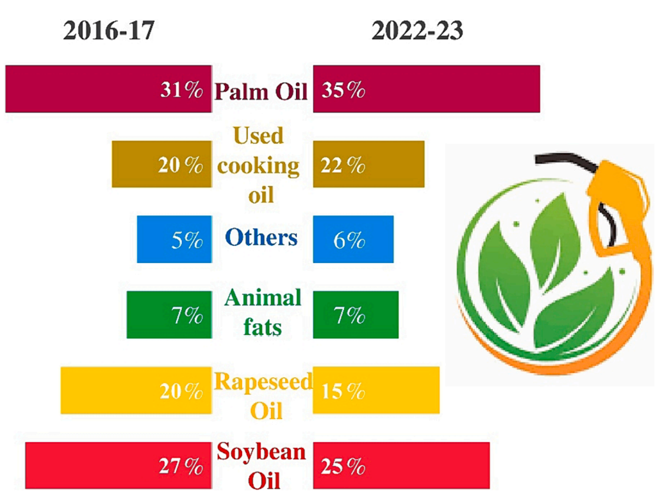

Fig. 8. Global biodiesel feedstocks comparison from 2016 to 2022.

microbial-driven degradation and associated corrosion.

2.2. Comparative analysis of biodiesel with conventional diesel

Biodiesel and conventional diesel are two dominant fuel options for diesel engines. A thorough comparison necessitates an in-depth analysis across various dimensions, encompassing their composition, environmental impact, engine performance, accessibility, storage and handling requirements, and economic viability [104]. Fig. 11 provides an overview of the key parameters considered for this analysis.

2.2.1. Biodiesel composition

The compositional distinction between biodiesel and conventional diesel fuels holds significant weight. Unlike its petroleum-derived counterpart, biodiesel boasts renewable origins, sourced from feedstocks like vegetable oils and animal lipids. Its inherent properties, including higher kinematic viscosity, density, and lower calorific value, have been extensively studied by various researchers [105–113] with the aim of optimizing engine performance and combustion efficiency, particularly at lower temperatures. This fundamental difference underscores biodiesel's renewable and ecologically sustainable credentials. Fatty acid methyl esters (FAME) and fatty acid ethyl esters (FAEE) constitute the primary building blocks of biodiesel. Their formation hinges on transesterification, a chemical process involving the reaction of feedstock triglycerides with an alcohol (typically methanol or ethanol), facilitated by a catalyst. Researchers have observed that a B20 blend (80 % diesel, 20 % biodiesel) demonstrably improved viscosity, density, and calorific value, leading to enhanced engine efficiency [78,114–116]. Lawan et al. [117] explored how bio-based additions affect biodiesel. These additives work best in raw materials with phenolic components, which affect antioxidation and freezing points. The composition of biodiesel, obtained from renewable sources, plays a significant role in its diminished environmental footprint and decreased reliance on fossil fuels. On the contrary, standard diesel's petroleum-based makeup, which highlights its connection to non-renewable resources and the environmental problems brought on by fossil fuel use, is generated from petroleum. Fatty acids affect the physico-chemical properties of biodiesel from processing through post-combustion. Before entering the market, biodiesel must meet international criteria like EN 14214 and ASTM D6751 to ensure fuel quality (Table 3) [118].

2.2.2. Environmental benefits of biodiesel

Biodiesel stands out as a fuel boasting superior environmental friendliness compared to conventional diesel, thanks mainly to its ability to effectively reduce greenhouse gas emissions and pollutant levels [124]. This characteristic has drawn substantial research interest within environmental studies since the 1960s [125]. Fig. 12 highlights several key environmental benefits associated with biodiesel use. Biodiesel's numerous environmental advantages make it an attractive substitute for traditional diesel fuel. Notably, it generates lower particulate matter emissions, contributing to improved air quality and public health. Studies have demonstrated that switching to biodiesel can demonstrably improve air quality in diesel-reliant cities. Trials using biodiesel-powered public transportation fleets improved AQI levels by 15 points [126]. Biodiesel reduces particulate matter emissions by 30–47 % compared to diesel fuels, according to studies [127–130]. According to Martin et al. [131], a B20 mix (20 % biodiesel, 80 % diesel) reduced

Table 1
Various generations of biodiesel feedstocks.

Feedstock Group	Feedstock	Significance	Limitation	References
Edible oil (Generation 1)	Rapeseeds oil, Palm oil, Castor oil, Hazelnut oil, Sunflower oil, Tigernut oil, Rice bran oil, Cashew oil, Radish oil, Pistachio, Walnut and Cotton seed oil, Soybean oil, and Mustard oil.	• Available and established. • Convert triglycerides to biodiesel. • Technological maturity.	• Competition for food crop land. • Possible deforestation. • High land-use need.	[39–41]
Non-edible oil (Generation 2)	Calophyllum inophyllum, Mahua India, Jatropha curcus, Thevettia peruviana, Crambe abyssinica, Sapindus mukorossi, Nagchampa, Jojoba, Rubber Seed, Nicotiana tabacum, Petroleum nut, Silk cotton tree, Karanja, Babassu tree, Tall oil, Milk bush.	• Reduces food supply competition. • Uses waste. • Possible increased yield per acre.	• Complex conversion methods. • Problems harvesting and processing biomass. • Feedstocks may compete for land.	[42,43]
Waste oils (Generation 3)	Fish, Chicken fat, Used culinary oil Thermal decomposition of biomass, animal fats, Algae Dunaliella salina, Botryococcus braunii, hen fat	• Very high production potential. • Diverse growth conditions, including wastewater.	• Costly production capital. • Harvesting and oil extraction issues. • Viability requires more research.	[44,45]
Advanced biodiesel (Generation 4)	Biodiesel is derived from photobiological solar energy, electrobiofuels, and synthetic cells.	• Possible direct biodiesel manufacturing. • Customized energy outputs. • It could use atmospheric CO_2.	• Mostly experimental. • Genetic modification ethics. • Technology is complicated.	[46,47]

Table 2
Different feedstock transesterification conditions.

Catalyst	Feedstock oil	Reaction temperature	Alcohol-to-oil ratio	Time	FAME yield	Refs.
Al_2O_3	Azolla pinnata	75	1:20	–	90.77	[68]
CaO catalyst	Microalgae	80	0.6:9	4 h	–	[69]
CeO_2-Fe_3O_4	Rapeseed	65	7:01	2	96.1	[70]
CuO nanoparticles	Pig tallow	–	1:29.87	35.36 min	97.82	[71]
EFB activated carbon	Waste cooking oil	70	1:12	2 h	97.1	[72]
Fe & Ca with pectin (FCP2)	Soyabean Oil	65	1:14	7.5	96.3	[73]
GO-NaOH-bentonite	Oleic acid	62	1:06	4.5	98.5	[74]
H_2SO_4	Chicken fat	50	1:30	30	99.01	[75]
KOH	Rubber seed	55	1:06		96.8	[76]
KOH	Castor	60	1:12	1	94.9	[77]
KOH	WCO	60	1:6	–	96.5	[78]
KOH	Beef tallow	60	–	1.5	95	[79]

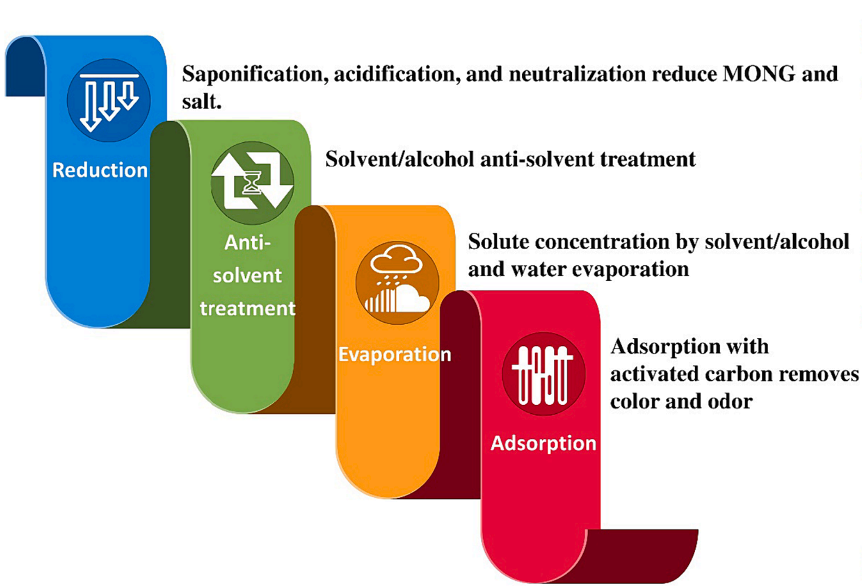

Fig. 9. Conventional refining steps for purification.

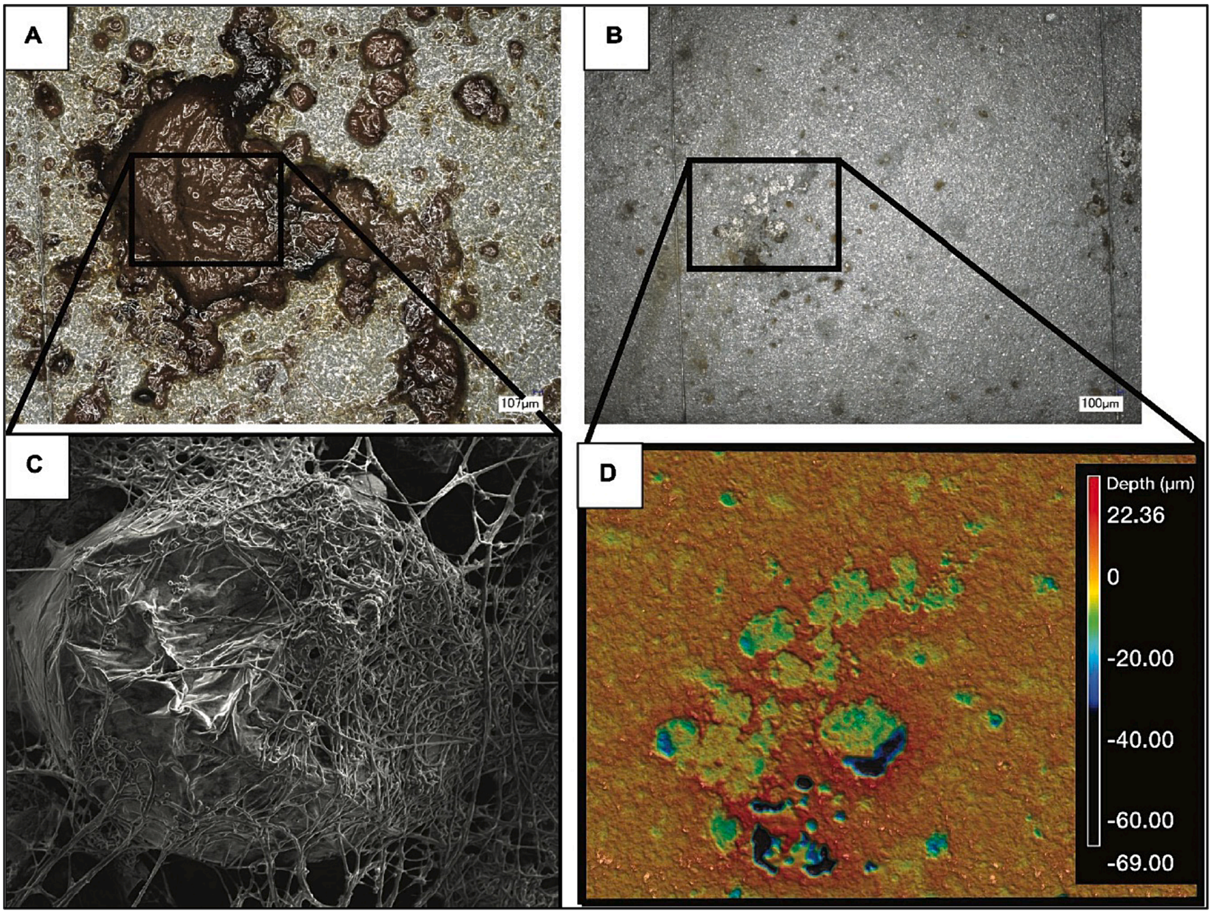

Fig. 10. Biofilm representative images (A). Witness coupon biofilm; cleaning this biofilm revealed corrosion pits; (B). SEM inspection of the uncleaned coupon showed several fungal filaments; (C) After cleansing, profilometry revealed pitting corrosion beneath the fungal layer (D) [102].

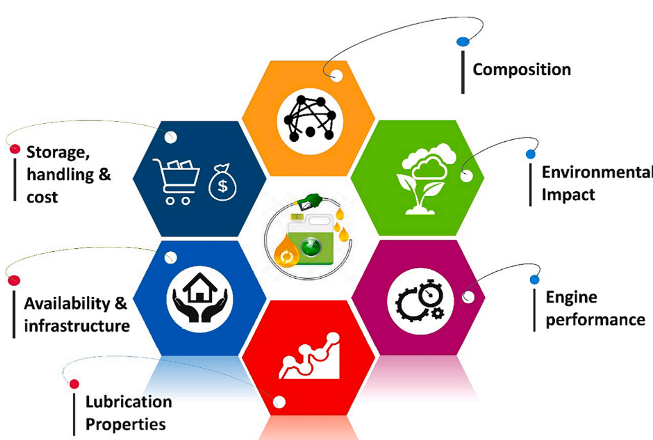

Fig. 11. Parameters considered for the analysis of biodiesel with conventional diesel.

particulate matter emissions by 20 %. Another study by How et al. [132], found a 35 % reduction with a B50 biodiesel blend. This phenomenon is especially advantageous in urban regions characterized by extensive utilization of diesel engines. Biodiesel use lowered PM2.5 levels by 12 Âµg per cubic meter. According to the World Health Organization, 10 Âµg per cubic meter drop in PM2.5 concentrations can reduce lung cancer mortality by 8 % [133]. The reduction in emissions leads to a decrease in respiratory ailments and contributes to improved air quality, hence enhancing the aesthetic attractiveness and overall healthiness of urban areas.

Using biodiesel also helps to decrease the amount of greenhouse gas emissions produced. Studies have shown that biodiesel cuts greenhouse gas emissions more than diesel. A lifecycle analysis by Castanheira et al. [134] found that soybean oil-based biodiesel reduces CO_2 emissions upto 57 % compared to conventional diesel. Another study Ashfaque et al [135] indicated that waste vegetable oil biodiesel reduced CO_2 emissions significantly. When burned, it releases CO_2; however, plants used in manufacturing sequester it through growth. This process renders biodiesel carbon–neutral, contributing to the mitigation of climate change. The net carbon emissions of biodiesel are practically neutral. In McLaughlin et al. [136], tons of CO_2 were absorbed during feedstock plant development for every ton emitted during biodiesel combustion, reducing net emissions to near zero. A fleet-level case study showed that switching a city’s public transportation to B20 biodiesel reduced CO_2 emissions by 15,000 tons per Year [137]. According to EPA estimates, this would remove 3,200 passenger cars from the road for a year. Biodiesel supports global climate goals [138]. As Rouhany and Montgomery [139], substituting 10 % of conventional fuel with biodiesel in transportation might reduce global CO_2 emissions by 2 %, helping meet Paris Agreement targets.

Biodiesel is more renewable and sustainable compared to fossil fuels. The material is derived from sustainable sources like vegetable oils or animal fats that can be replenished. This stands in stark contrast to fossil fuels, which are finite resources and pose gro wing challenges and environmental harm during the extraction process. The USDA estimates that one acre of soybeans produces 60 gallons of biodiesel [140]. However, an oil field would need several acres to make the same quantity of fossil diesel, depleting a non-renewable resource. Biodiesel

Table 3
EN 14214 and ASTM D 6751 biodiesel specifications [119–123]

	ASTMD 6751		EN 14,214	
Property(unit)	Standard	Limit	Standard	Limit
Acid number(mg KOH/g)	EN 14,104	0.5(max.)	ASTM D664	0.5(max.)
Carbon residue on 10 % distillation residue	EN OSO 10370	0.30 mol/mol% (max.)	ASTM D 4530	0.05 wt% (max.)
Cetane number(-)	EN ISO 5165	51(min.)	ASTM D613	47(min.)
Cloud point(°C)	EN ISO 23015	According to national specifications	ASTM D2500	Inform customer
Cold filter plugging point(°C)	–	By place and season	ASTM D6371	Not specified
Copper strip corrosion	EN ISO 2160	Class 1 rating (max.)	ASTM D130	Class 3 (max.)
Density at 15 °C (kg/m3)	EN ISO 12185EN ISO 3675	860–900	ASTM D4052-91	870–890
Diglycerides(wt%)	EN 14,105	0.20(max.)	–	–
Distillation at 360 °C(vol.%)			ASTM D1160	90(max.)
Free glycerin(mol/mol%)	EN 1405/14016	0.02(max.)	ASTM D6584	0.02 (max.)
Flashpoint(°C)	EN ISO 3679	101(min.)	ASTM D93	130(min.)
Heat value(MJ/kg)	DIN 51900–1/2	35(min.)	–	–
Iodine value(g/100 g)	EN 14,111	120(max.)	–	–
Kinematic viscosity at 40 °C(mm2/s)	EN ISO 3104	3.5–5.0	ASTM D445	1.9–6.0
Monoglycerides(wt %)	EN 14,105	0.80(max.)	ASTM D6584	0.40 (max.)
Metals Group I(K + Na)(mg/kg)	EN 14,538EN 14,109EN 14,108	5(max.)	EN 14,538	5(max.)
Metals Group II(Mg + Ca)(mg/kg)	EN 14,538	5(max.)	EN 14,538	5(max.)
Methanol percent (mol/mol%)	EN 14,110	0.20(max.)	EN 14,110	0.20 (max.)
Oxidation stability at 110 °C(h)	EN 14,112	6(min.)	EN ISO 14112	3(min.)
Phosphorus(mg/kg)	EN 14,107	10(max.)	ASTM D4951	10(max.)
Polyunsaturated methyl esters(wt %)	EN 15,779	1(max.)	–	–
Pouring tempreture (°C)	–	–	ASTM D97	Not specified
Sulfated ash(mol/mol%)	EN ISO 3987	0.02(max.)	ASTM D874	0.02 (max.)
Total glycerol(mol/mol%)	EN 14,105	0.25(max.)	ASTM D6548	0.24 (max.)
Triglycerides(wt%)	EN 14,105	0.20(max.)	–	–
Water content and sediment	EN ISO 12937	0.05 wt%(max.)	ASTM D2709	0.050 vol %(max.)

feedstocks like soybean and canola oils regenerate in 90–150 days. However, fossil fuels like crude oil form over millions of years. A study by Tahat et al., [141] found that well-managed agricultural methods can sustain high-yield feedstock production year-over-year without deteriorating soil quality. Another relevant indicator is energy ROI. A report by Propane et al. [142] found that biodiesel generates 4.56 units per unit of energy utilized in its manufacturing. This ratio is 3:1 for fossil diesel, showing that biodiesel is more energy-efficient. Furthermore, the production and utilization of biodiesel can help alleviate resource scarcity. As per the Luque et al. [143] replacing 20 % of conventional diesel with biodiesel might cut water usage over the fuel's lifespan by 35 %. The utilization of biodiesel diminishes our reliance on limited resources,

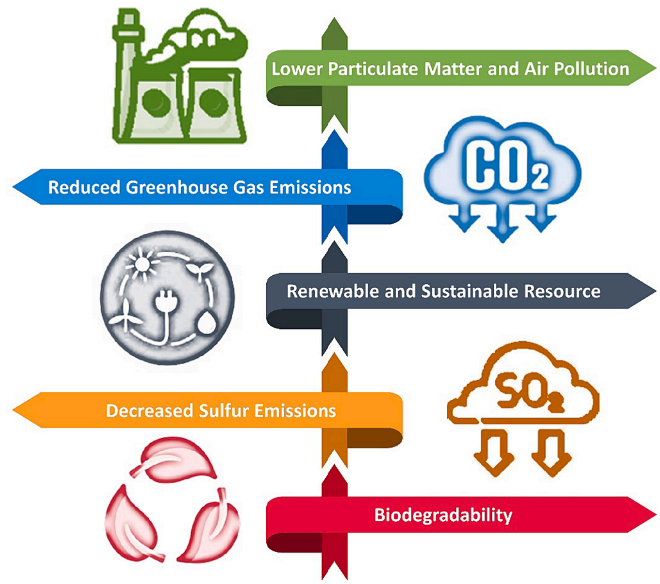

Fig. 12. Environmental benefits of biodiesel.

hence enhancing the sustainability of our energy systems.

Furthermore, using biodiesel leads to lower sulfur dioxide emissions due to its reduced sulfur content. The EPA says standard diesel fuel includes up to 500 ppm sulfur. Biodiesel meets ultra-low-sulfur diesel (ULSD) specifications with sulfur levels below 15 ppm [144]. SO_2 emissions are directly related to sulfur content, according to studies. Going from diesel to biodiesel reduces SO_2 emissions by 99 %, according to Martikainen et al. [145]. The significant decrease in emissions enhances the air quality and mitigates problems related to respiratory difficulties and acid rain. A lifecycle evaluation found that biodiesel could reduce sulfur oxide (SOx) emissions by 40 % or more, depending on feedstock [146]. This measure reduces air pollution and mitigates the health concerns connected with sulfur emissions, including respiratory problems and smog formation. Air quality requirements and international sulfur emission agreements require these reductions. A 2019 study found that a 50 % reduction in sulfur emissions might prevent 5,000 cases of bronchitis and 3,000 respiratory hospital admissions annually [147].

It is worth mentioning that biodiesel is biodegradable. In the event of spills, the rate of degradation of this particular substance is accelerated compared to that of traditional diesel, hence reducing the extent of environmental harm. When released into the environment, biodiesel degrades 85–88 % in 28 days, according to NREL research [148]. In contrast, regular diesel degrades by 26 % during the same period [149]. The product's biodegradability supports sustainability goals and enhances safety. According to Folino et al. [150], natural microorganisms may break down 95 % of biodiesel into water and carbon dioxide in 21 days. Biodegradation was two to five times faster than ordinary diesel. Mariano et al. [151] , found that biodiesel's superior biodegradability might cut soil and water cleaning expenditures by 50 % compared to diesel spills. Biodiesel's biodegradability reduces long-term environmental risks. Biodiesel-contaminated soil recovered 70 % faster than diesel-contaminated soil [152].

Ndong et al. [153] examined West African *Jatropha curcas* biofuel lifecycles. This biofuel lowered greenhouse gas emissions by 72 % more than ordinary diesel. One primary benefit of biodiesel is its capacity to mitigate CO_2 emissions throughout combustion. The combustion of biodiesel results in the emission of carbon into the atmosphere, which is subsequently counterbalanced by the carbon sequestration that occurs during the growth of the plants used in its production. Biodiesel combustion emits less net CO_2 than fossil fuel-derived diesel, which has a carbon offsetting mechanism. Hosseinzadeh Bandbafha et al. [154]

found biodiesel additions could improve its environmental profile. Cavalcanti et al. [155] examined diesel/biodiesel engines and found relationships between economic parameters, exergy destruction, and biodiesel concentration. The sulfur and particle count in biodiesel are lower than those in diesel. Sulfur in diesel gasoline breaks down into SO_2. The atmospheric pollutant SO_2 is well-known for harming people's health and the delicate balance of the natural world. As the sulfur content of biodiesel has been shown to decrease steadily, SO_2 emissions have declined in direct proportion. Particulate matter, often known as fine particles, is another pollutant created when diesel fuel is burned, and its adverse effects on human health and the environment are well-known. Yang [156] stressed supply chain economics in lifecycle assessments, while Rosen [157] recommended a comprehensive approach to biofuel evaluations that includes economic, environmental, and exergy considerations. These particulate matter elements have the potential to impact the atmospheric composition negatively, consequently degrading air quality, human well-being, and overall health.

Based on empirical research, it has been determined that biodiesel exhibits a lower emission of particulate matter than conventional diesel, thereby leading to enhanced air quality and decreased potential health hazards [158]. *Ceiba pentandra* oil produces biodiesel using lipase immobilized on mesoporous material as a catalyst. Pooja et al. [159] investigated the performance of biodiesel from kapok (*Ceiba pentandra*) oil. Kapok B20 at full load, Kapok methyl esters emit 13.7 % less CO_2 than diesel due to their higher oxygen and lower carbon content (Fig. 13 A). B20 blend CO emissions declined 5.08 % at full load compared to diesel (Fig. 13 B), supporting prior findings by authors [160]. Kapok B20 reduces full-load diesel emissions by 8.4 % (Fig. 13 C). Biodiesel's greater combustion temperature owing to oxygen content increases NOx emissions by 31 % compared to diesel (Fig. 13 D). NOx emissions rise with combustion temperature and oxygen supply [161].

Biodiesel presents significant environmental benefits in comparison to traditional diesel fuel. Reducing carbon dioxide emissions, facilitated by carbon offsetting through plant absorption, contributes to the amelioration of climate change [162]. Moreover, the diminished concentration of sulfur and decreased presence of particulate matter in the substance enhances air quality and promotes human welfare [163]. The environmental advantages of biodiesel render it a compelling substitute fuel in the pursuit of more sustainable and environmentally friendly energy solutions by societies [164].

2.2.3. Engine performance

Despite presenting several similarities to conventional diesel, enabling its use in diesel engines with minimal modifications, biodiesel possesses crucial differences that require consideration [165]. One notable distinction is its higher cetane number, a measure of a fuel's ignition quality. Higher values indicate better ignition properties. Consequently, biodiesel typically offers improved combustion efficiency and reduced engine noise, contributing to enhanced driving comfort. However, its slightly lower energy content compared to conventional diesel implies that pure biodiesel may lead to a minor decrease in fuel efficiency [166]. This reduced energy density translates to a potentially higher volume of biodiesel needed to generate the same power output as conventional diesel. Another critical factor is biodiesel's increased viscosity, its resistance to flow. Biodiesel exhibits higher viscosity than conventional diesel, posing potential challenges, particularly in colder climates [167]. This can lead to difficulties with fuel flow and atomization, potentially causing fuel system issues like clogged filters or injector deposits. To address these challenges, engine adjustments or biodiesel blends with conventional diesel might be necessary in colder

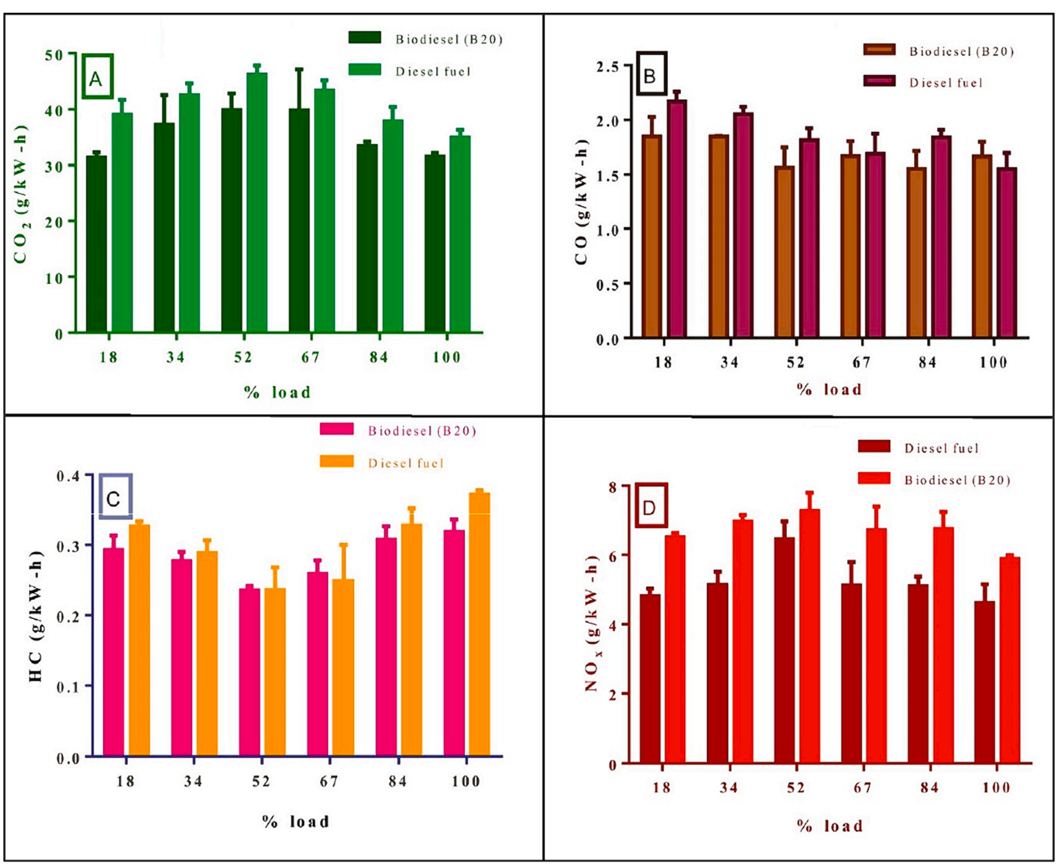

Fig. 13. Ceiba pentandra oil biodiesel emissions. (A) Diesel and biodiesel mix (B20) CO_2 emissions at different loads. (B) CO emission variation at different loads for diesel and biodiesel blends (B20). (C) Diesel and biodiesel mix (B20) HC and emission variations at varied loads. (D) NOx emission variation at different loads for diesel and biodiesel blends (B20) [159] (Adapted with permission from Elsevier BV with License No,: 5723470848926).

environments. However, it is important to note that many modern diesel engines are engineered to handle biodiesel blends and effectively mitigate these potential problems [168]. Engine manufacturers continuously refine their designs to ensure compatibility and optimize performance.

Inconsistent trends are observed in Fig. 14(a)-(d) regarding NOx, CO, CO_2, and HC percentage changes compared to reference values, as evidenced by the disparities across experimental setups implemented by different researchers. Monyem et. al. [169] found that oxidized biodiesel improves exhaust pollutants while retaining engine performance. Oxidized biodiesel emits 15 % less CO than unoxidized and 28 % less than No. 2 diesel. Oxidized biodiesel reduced HC emissions by 21 % and 54 % compared to unoxidized and No. 2 diesel. Engine load, speed, Cetene number, and other parameters strongly impact CO emissions. Engine speed reduces biodiesel CO emissions. Fig. 4 compares HC emission to references. The figure demonstrates a maximum 55 % HC reduction. Most studies show biodiesel reduces HC emissions. HC emissions are reduced by biodiesel injection and combustion, however, engine load effects vary. Metal-based biodiesel additions less improve HC emissions. Small amounts of ethanol and methanol in biodiesel and diesel may minimize HC emissions [170]. BMEP raised exhaust gas temperature, BTE, SO, CO_2, HC, and CO emissions. Biodiesel has a higher BSFC than diesel at ORG INHN (4-hole nozzles). This may be because biodiesel has a lower LHV than diesel. Due to higher combustion, biodiesel or its mixes lowered SO, CO, and HC emissions and increased CO_2 emissions at ORG INHN [171].

2.2.4. Lubrication properties

A key advantage of biodiesel over conventional diesel is its superior lubricating properties. Biodiesel exhibits increased lubricity, which signifies its ability to reduce friction and wear in an engine's fuel system components [173]. This improved lubrication can be particularly beneficial for older engines or those with high mileage. Kumar et al. [174] tested blends of jatropha biodiesel with four-ball tester. As biodiesel concentration increased and load and temperature decreased, fuel lubricity improved. Fazal et al. [175] examined palm oil biodiesel (B100, B50, B20, and B10) wear and friction for load at 600, 900, 1200, and 1500 rpm. As the biodiesel ratio increased, a concomitant decrease in wear and friction was observed, leading to reduced wear on sliding components. Biodiesel's enhanced lubricating properties contribute to the protection of fuel system elements like pumps, injectors, and valves, which rely heavily on adequate lubrication for optimal function and lifespan [176]. Li et al. [177] examined how biodiesel composition affects lubricity from fourteen oil sources using high-frequency reciprocating rig testing and gas chromatography to determine abrasive spot sizes. They also measured biodiesel's grinding point diameter and chemical makeup. Methyl stearate, linoleate, oleate, and palmitate made up 92.18 % of biodiesel. In biodiesel testing, prickly ash methyl ester had the greatest grinding point diameter (187.35 μm) and rubber seed methyl ester had the least (169.71 μm). The linear model predicted worn point diameter with a significant correlation (R = 0.91). Biodiesel holds promise for improved engine performance by reducing friction and wear, leading to smoother operation, reduced engine noise, and potentially extended component lifespan [178]. However, it is crucial to

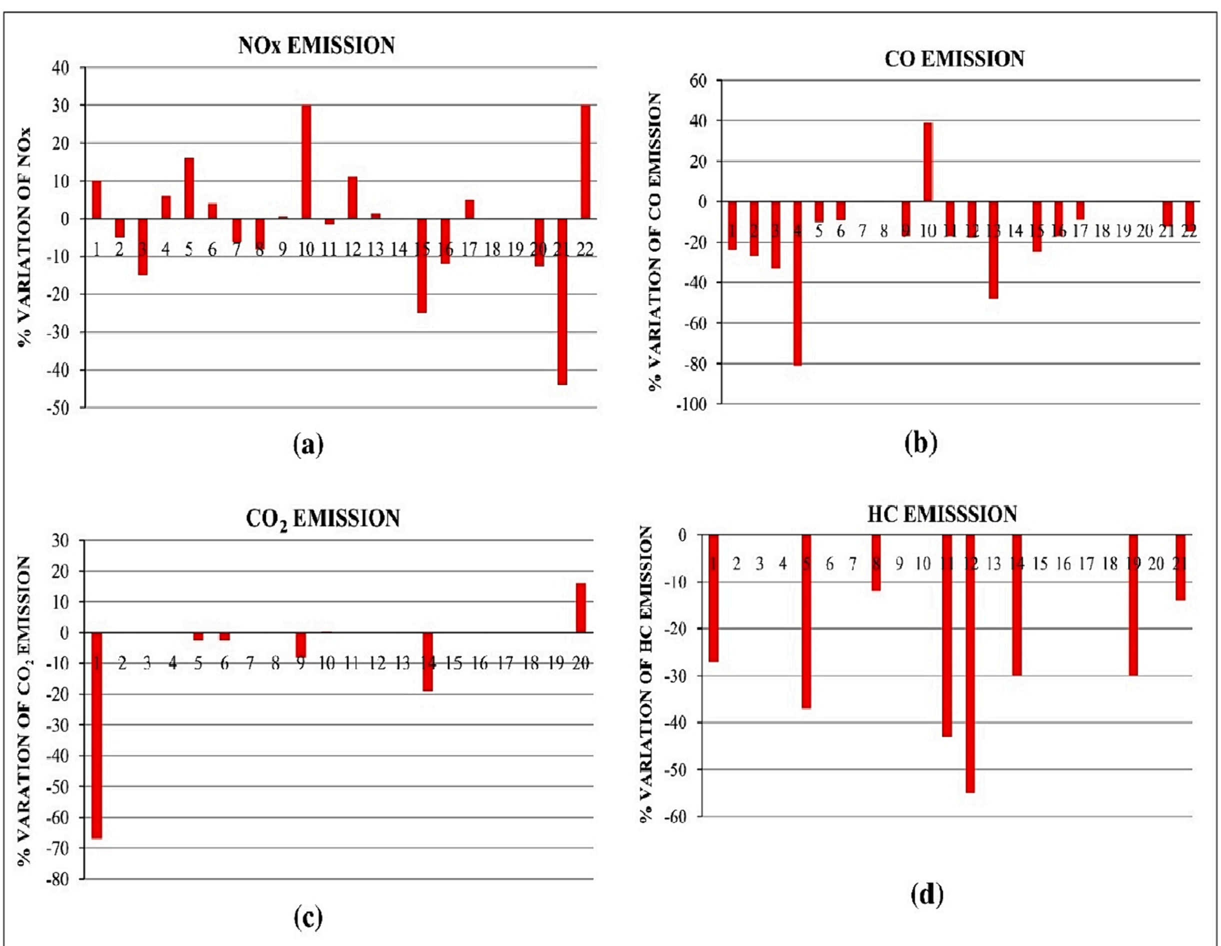

Fig. 14. Proportion of (a) NOx, (b) CO, (c) CO_2, and (d) HC in the exhaust of a CI engine with biodiesel mixes compared to diesel-fueled engine [172] (Adapted with permission from Elsevier BV with License No,: 5723470696934).

recognize that while biodiesel's enhanced lubrication boasts benefits, it can also lead to increased fuel system deposit buildup over time if proper maintenance isn't prioritized. The very lubricating properties that benefit the engine can promote the accumulation of deposits on critical components like fuel injectors [179]. These deposits can then impede fuel flow and compromise engine performance. Chourasia et al. [180] found that B20A4-fueled engines wore less than diesel-fueled engines. Regression was proposed to forecast engine wear. To anticipate engine wear, the regression model might be expanded. The lubricating oil sample had 640 mg kg − 1 of metal debris (predicted using regression model) for diesel and 420 mg kg − 1 for B20A4, respectively. Regular maintenance practices are essential in order to reduce the risk of fuel system deposits. The recommended practices for maintaining the fuel system involve periodic cleaning, utilization of high-quality fuel filters, and adherence to the manufacturer's guidelines for fuel system maintenance [181]. By adhering to these practices, one can effectively mitigate the potential challenges linked to heightened lubricity and uphold the engine's performance and efficiency while utilizing biodiesel. High-frequency reciprocating friction and wear testing machines (HFRR) analyze biodiesel lubrication [182,183]. Sukjit et al. [184] found that reducing unsaturated molecules in H-FAME reduced humidity sensitivity. With increased biodiesel concentration, Xiao et al. [185] found that steel balls for steel–steel contact had less wear scars. Hosseinpour et al. [186] estimated biodiesel CN from FAMES. A detailed examination of biodiesel content and modified abrasive spot diameter allows for more objective quality assessment. This can help expand biodiesel use and commercialization, supporting national renewable energy, energy conservation, and emission reduction efforts. Gupta et al. [187] conducted a comprehensive investigation into the prolonged material compatibility of blends containing Karanja oil methyl ester (biodiesel) with common rail direct injection system-equipped diesel engine commonly employed in SUVs.. KB20-fueled engines had lower valve and crankpin wear but increased wear on liners, piston rings, pistons, gudgeon pin, connecting rod small and big end bearings, and main bearings. Fuel chemistry influenced lubricating oil performance and lifespan. The cylinder liner's surface roughness was assessed before and after the endurance test to evaluate wear during both phases. Compared to piston top, cylinder head, and injectors, KB20-fueled engine pistons had more carbonaceous deposits as shown in Fig. 15.

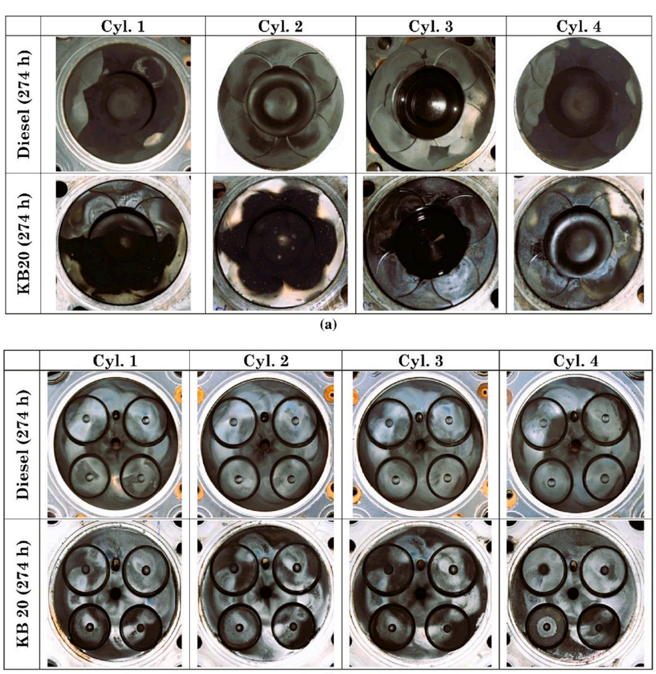

Fig. 15. Carbon deposits on engines (a) Piston crowns of KB20 and mineral diesel fuelled, (b) cylinder head of diesel and KB20 fuelled [187] (Adapted with permission from Elsevier BV with License No,: 5723470543478).

It is worth highlighting that modern diesel engines and fuel systems are designed specifically to handle biodiesel blends, potentially exhibiting increased resistance to deposit buildup. Additionally, employing biodiesel-specific fuel additives can effectively mitigate deposit formation and maintain optimal fuel system cleanliness.

2.2.5. Availability, infrastructure, storage and handling

The choice between biodiesel and diesel fuel hinges on the region's existing infrastructure and fuel availability [188]. Conventional diesel, with its established global infrastructure and readily accessible fuel stations, holds an undeniable advantage [189]. In contrast, biodiesel availability is a function of production capacity and location. Initially, limited production and distribution networks hampered biodiesel accessibility [190]. However, recent years have witnessed a significant increase in biodiesel availability, fueled by national policies promoting its production and the expansion of storage and distribution infrastructure [191]. Local production has also played a crucial role in minimizing reliance on long-distance transportation [192].

Fuel stations now offer a wider array of eco-friendly options, including biodiesel blends, readily accessible through dedicated pumps [193]. Collaborative efforts by governments, fuel producers, and industry partners are actively improving biodiesel infrastructure to enhance both demand and quality. While not yet as ubiquitous as diesel, biodiesel's burgeoning infrastructure and undeniable environmental benefits hint at a promising future [194]. As infrastructure continues to evolve, renewable fuels like biodiesel will become increasingly accessible, contributing to a more sustainable energy system [195].

Compared to diesel, biodiesel demands meticulous handling and storage. To ensure safety and prevent mishaps, adhering to proper storage and handling protocols is paramount [196]. Unique features render biodiesel susceptible to oxidation and breakdown, necessitating stringent quality and stability standards. Its faster oxidation rate compared to diesel, driven by oxygen and moisture, leads to sediment and undesirable byproducts. To avert contamination, storing biodiesel in sealed tanks of either stainless steel or HDPE is crucial [197]. High oxygen exposure diminishes biodiesel's shelf life, significantly less than its diesel counterpart. Implementing proper storage temperatures and fuel rotation strategies can effectively extend the lifespan of biodiesel [198].

Biodiesel requires meticulous handling to preserve its quality. Maintaining equipment cleanliness is crucial to prevent cross-contamination between surfaces and components [199]. Biodiesel requires meticulous handling to preserve its quality. Maintaining equipment cleanliness is crucial to prevent cross-contamination between surfaces and components [200]. The inherent sustainability of biodiesel as a fuel necessitates heightened vigilance during storage and handling [201]. Adapting industry standards and regulations continuously enhances biodiesel storage and handling practices, ensuring its reliability as a viable diesel substitute.

2.2.6. Cost of biodiesel

The overall cost of biodiesel production hinges on several factors, including feedstock pricing, production quantities, and government subsidies. In general, biodiesel production incurs higher costs than conventional diesel, largely due to the additional processing stages involved. Feedstock costs, dictated by feedstock prices, play a crucial role in determining the final cost. Several reports [202–207] indicate that feedstock acquisition comprises over 75 % of total biodiesel manufacturing expenses, as illustrated in Fig. 16. The accessibility and cost of feedstocks like vegetable oils and animal fats fluctuate based on factors like crop yields, weather conditions, and global market dynamics [208]. Gaurav et al. [209] conducted a comparative analysis of the financial performances of various methods aimed at the synthesis of

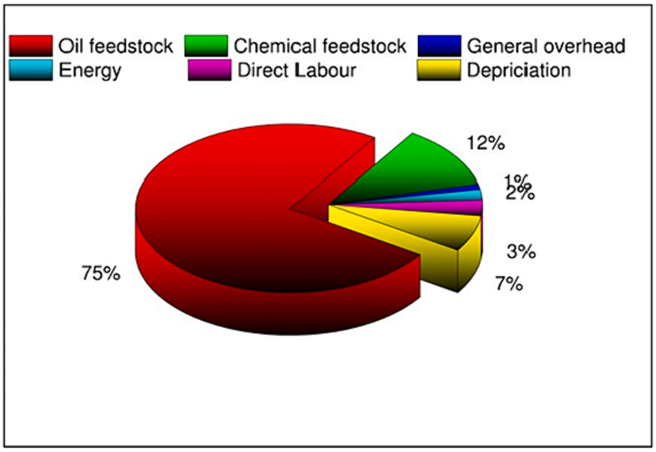

Fig. 16. Common biodiesel production costs.[446] (Adapted with permission from Elsevier BV with License No.: 5756370599070)

biodiesel from waste cooking oil. The methods under investigation were the Catalytic Distillation (CD) method and the conventional reactor separation method. Heterogeneous acids catalyzed both reactions. Implementing the catalytic distillation process can minimize the necessary equipment by circumventing the need for both the flash separation unit and plug flow reactor, which are typically essential components in the conventional reactor plus separation configuration. This phenomenon resulted in a notable decrease in capital and production expenses, rendering this technical alternative economically viable. Alterations in the prices of the feedstock can have an effect on the overall cost of manufacturing biodiesel. The amount of biofuel made has a direct effect on how much it costs. Because of economies of scale, increasing output usually leads to lower unit manufacturing costs [210]. Another research has demonstrated the valorization of waste cooking oils (WCO) and Ca-rich seafood wastes as alkaline heterogeneous catalysts to produce FAME biodiesel, offering a sustainable solution to reduce greenhouse gas emissions and utilize renewable biomass energy sources while overcoming the limitations of catalytic homogeneous processes [211]. As the biodiesel industry expands, manufacturing capacities will increase, resulting in lower per-unit prices in the near future. Government incentives and policies can have a significant impact on biodiesel prices [212]. Gebremariam et al. [213] present an economics of biodiesel production, with a particular emphasis on methodologies for evaluating investment and operation costs, evaluating economically superior technology, catalyst, and feedstock options, and highlighting profitability and system variables that affect biodiesel production. Table 4 presents an overview of several studies conducted to assess the economic implications associated with the production of biodiesel utilizing diverse technological approaches. To promote biodiesel production and consumption, many governments have passed subsidies, tax incentives, and green fuel regulations. These incentives may narrow the price differential between biodiesel and ordinary diesel, making it more economically viable and enticing to producers and consumers. As technology develops and becomes more efficient, biodiesel manufacturing costs should decrease [214]. Improvements in feedstock availability, catalyst efficiency, and manufacturing method optimization are at the forefront of current research and develpment efforts. The manufacture of biodiesel may become less expensive as a result of these initiatives. Biodiesel manufacturing costs are now larger than conventional diesel production expenses. The price of biodiesel is affected by many variables, such as the cost of feedstock, the scale of production, and any applicable government subsidies [215]. With advancements in technology, increased production capacity, and the implementation of favorable policies, it is anticipated that the cost of biodiesel will become more comparable to that of conventional diesel. This development will enhance the economic feasibility of biodiesel as a renewable fuel alternative.

Table 4
Cost analyses for biodiesel production utilizing various techniques and feedstocks.

Feedstock	Capacity	Production technology type	Production cost $/ton	Ref
Waste cooking oil	8000 tons/ year	Transesterification catalyzed by lipase (Novozym-435)	1047,97	[216]
Waste cooking oil	8000 tons/ year	Methanol transesterification catalyzed by H_2SO_4	750,38	[216]
Waste cooking oil	8000 tons/ year	Transesterification with methanol catalyzed by KOH	868,60	[216]
Palm oil	1000 tons batch mode	Lipase catalyst process immobilization	2414,63	[217]
Palm oil	1000 tons batch mode	Process of soluble lipase catalysis	7821,37	[217]
Palm oil	1000 tons batch mode	Process with alkali catalyst	1166,67	[217]
Microalgae oil	Continuous reactor (30 °C)	Catalysis by homogeneous H_2SO_4 with Self-produced regenerated glycerol feedstock	580	[218]
Microalgae oil	Continuous reactor (30 °C)	Catalysis by homogeneous H_2SO_4 with purchased feedstock	620	[218]
Waste cooking oil	1452 tons/ year in batch mode	Vacuum FAME distillation process with Heterogeneous CaO catalyst	969	[219]
Waste cooking oil	1452 tons/ year in batch mode	Hot water purification process with Heterogeneous CaO catalyst	911	[219]
Waste cooking oil	1452 tons/ year in batch mode	vacuum FAME distillation process with Homogeneous KOH catalyst	984	[219]
Waste cooking oil	1452 tons/ year in batch mode	hot water purification process with Homogeneous KOH catalyst	921	[219]
Waste cooking oil	7260 tons/ year in batch mode	Vacuum FAME distillation process with Heterogeneous CaO catalyst	622	[219]
Waste cooking oil	7260 tons/ year in batch mode	Hot water purification process with Heterogeneous CaO catalyst	584	[219]
Waste cooking oil	7260 tons/ year in batch mode	vacuum FAME distillation process with Homogeneous KOH catalyst	641	[219]
Waste cooking oil	7260 tons/ year in batch mode	hot water purification process with Homogeneous KOH catalyst	598	[219]

2.3. Challenges and limitations of biodiesel usage

Biodiesel has environmental benefits but also has drawbacks that must be considered. To comprehensively analyze the viability and efficacy of a particular fuel source, it is necessary to consider multiple factors [220]. The significant challenges are shown in Fig. 17, which mainly include feedstock availability and competition, land utilization and environmental impacts, lifespan evaluation, engine compatibility and performance, infrastructure and distribution needs, cost, and fuel quality and standards. The challenges described above highlight how important it is to acquire sustainable feedstock sources, implement

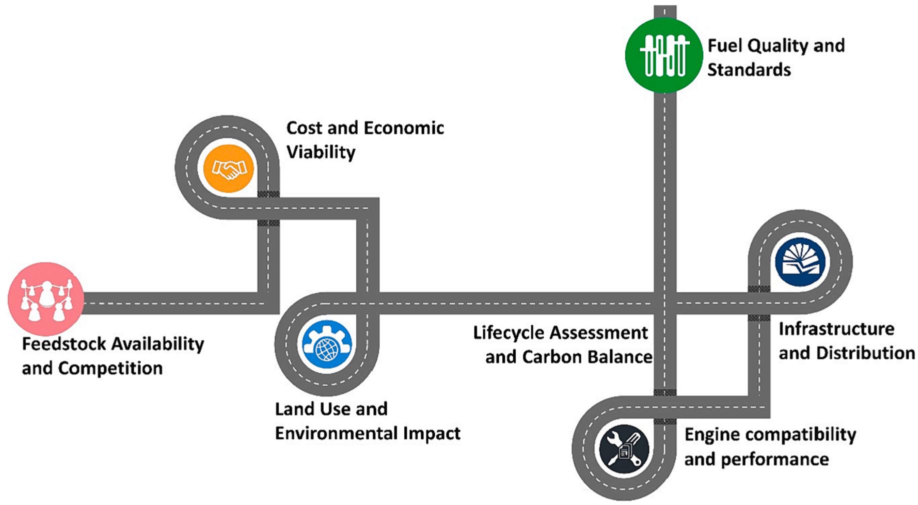

Fig. 17. Challenges and limitations of biodiesel usage.

responsible land use practices, conduct thorough assessments of the entire lifecycle, make any necessary modifications to engines, develop infrastructure, optimize costs, and implement quality control measures [221]. By effectively tackling these challenges above, biodiesel has the potential to solidify its position as a feasible and environmentally friendly alternative fuel choice.

2.3.1. Feedstock availability and competition

While biodiesel offers environmental benefits over diesel, its adoption presents an array of challenges. Derived from vegetable oils, animal fats, and recycled cooking oil [222], its production is susceptible to various external factors, including fluctuations in agricultural yields driven by climate change and demand from the food and bio-based industries [223]. Statistics suggest these feedstocks compete with food crops for arable land, a concern amplified by biodiesel's reliance on soybean oil, which constitutes 30 % of global vegetable oil production and strains existing food supply chains [224]. Moreover, the pricing and cost-efficiency of biodiesel production hinge heavily on feedstock reliability. Biofuel cropland area is projected to surge from 19.7 million hectares in 2010 to a staggering 32.3–82.1 million by 2030 [225]. Striking a delicate balance between energy production and sustainable land use is crucial, as competition between food and biofuel crops threatens both food security and environmental sustainability. The USDA reported a 28 % increase in soybean oil prices, from 52.66 cents per pound in January 2020 to 67.75 cents per pound in January 2021, partly attributable to biodiesel production [226]. This highlights the need for careful feedstock management to mitigate environmental damage. Enhancing biodiesel sustainability necessitates exploring alternative feedstocks like non-edible oil crops, algae, and waste materials, which require fewer resources and avoid competition with the food supply chain [227].

2.3.2. Land use and environmental impact

Land use and environmental effects are significant issues. Biodiesel feedstock cultivation on unsustainable land may degrade the environment. Converting forests into areas for growing feedstock crops can disrupt biodiversity and contribute to higher greenhouse gas emissions [228]. Converting natural vegetation or forests to biofuel feedstocks creates a 'carbon debt' that can take years to settle [229]. Sustainable land management is needed because palm oil deforestation, another biodiesel source, has increased tropical deforestation emissions by 10 % [230]. The heavy use of water and agrochemicals in feedstock farming may also pollute water sources [231]. Agroforestry, managing land to prevent erosion, and investigating damaged sites can address these issues. Develop low-impact feedstocks and alternative production methods to reduce land use and environmental impacts, making biodiesel a sustainable fuel [232]. Non-food biomass and other feedstocks like algae, which may produce 5,000 to 15,000 gallons of biofuel per acre compared to 50 gallons for soybeans, are being explored to address these challenges [233]. These alternatives need technological advances and commercial validation to succeed.

2.3.3. Lifecycle assessment and carbon balance

A lifecycle assessment (LCA) is needed to examine biodiesel's environmental impact, including greenhouse gas emissions from manufacturing and consumption. The challenges associated with these resources have significant implications for their environmental viability [234]. Liu et al. [235] examines bioethanol and biodiesel life cycle assessments, finding considerable fossil energy consumption and GHG emissions unpredictability. System boundaries and allocation technique strongly affect LCA results. System boundaries—cradle-to-grave, cradle-to-gate, or gate-to-gate—also provide a challenge, depending on study goals. From biomass production to the processing, use, and disposal of biofuel or bioproducts, a cradle-to-grave approach covers the complete lifecycle. However, cradle-to-gate assessments are often used to compare biomass-based bio-based products. When researching an innovative processing technique, gate-to-gate evaluations are helpful [236]. Pikula et al. [237] analyzes standard and innovative biodiesel production and consumption technologies, highlighting microalgal lipid synthesis, transesterification, and microwave/ultrasound developments. The carbon balance can be affected by changes in land use, agricultural practices, and the energy consumed during the processing and transportation of feedstock. The issue of carbon sequestration and the delay between carbon dioxide absorption and its release into the atmosphere is particularly relevant in bio-based energy and materials. Martin-Gamboa et al. [238] and Levasseur et al. [239] have discussed the importance of factoring in these considerations. LCAs show where improvements can minimize carbon footprints. Biodiesel environmental impact judgments are made easier with standard LCA procedures. The representativeness and uncertainty of LCA outcomes are significantly influenced by time. It has a substantial impact on them. Maciel et al. [240] cite the time required to neutralize land use change impacts as a prime example.

2.3.4. Engine compatibility and performance

Engine compatibility and performance are essential for biodiesel. Biodiesel use in diesel engines has been proven to affect the injection system, including swelling of the elastomeric seals in injection distribution, which can cause fuel leakage [241]. Biodiesel's solvent characteristics may degrade some engine components [242]. Biodiesel can accelerate the corrosion of copper and brass by up to 50 % [242]. In colder climates, biodiesel's higher viscosity may impair fuel flow and engine performance, requiring engine adaptations. B100′s CFPP can reach 0 °C, limiting its application in colder climates without additions or blending [243]. Poor atomization increases particle emissions by 20–30 % [244]. Biodiesel has improved lubricity, resulting in 30–50 % fewer wear scars, although its long-term effects on engine wear are unclear and need further study [245]. The specific fuel consumption was higher for biodiesel blends due to their lower heating value compared to diesel [246]. Biodiesel has a lower energy content than diesel, which may affect fuel efficiency. The energy content of biodiesel is 8–10 % lower than regular diesel fuel, resulting in a 5–7 % loss in engine power output and fuel economy [247]. However, engine makers are improving biodiesel blend compatibility. Higher combustion temperatures can increase NOx emissions by up to 10 % from biodiesel, but PM, CO, and HC emissions typically drop by 15–20 % [248]. Fuel standards and manufacturer recommendations improve engine performance and lifetime. Engine compatibility and performance can help users choose biodiesel for their engines. Optimizing engine selection, maintenance, and fuel management maximizes biodiesel benefits and mitigates potential drawbacks.

2.3.5. Infrastructure and distribution

Infrastructure and distribution issues limit biodiesel utilization. Existing fuel infrastructure is designed for conventional diesel, which is less corrosive than biodiesel [249]. Due to its susceptibility to oxidation and decay, biodiesel requires specific storage and handling facilities. Transporting and blending require particular equipment and cooperation. During transportation, biodiesel's hygroscopic nature can cause microbial growth and fuel breakdown due to increased water absorption [250]. Kamil et al. [251] found that long-distance biodiesel shipping can increase moisture content by 0.2 %, exceeding ASTM D6751. Biodiesel has a shorter shelf life than diesel due to its lower oxidative stability [252]. Additional blending facilities are required to produce different biodiesel blends, which increases infrastructure expenses. A biodiesel blending terminal can cost up to $2 million, according to cost-benefit analysis [253]. Under optimum conditions, B100 storage life is 6 months, compared to 12 months for diesel, before degradation impairs quality [254]. The biodiesel supply chain is vulnerable to disturbances caused by feedstock shortages. Mueller et al. [255] found that agricultural fluctuations can affect biodiesel production costs by 10 %-15 %. Competition with established gasoline distribution networks is a significant obstacle in the market. In economic model, a 10 % drop in crude oil prices reduced biodiesel demand by 15 % [256]. Because biodiesel is more expensive than standard diesel, there is a higher danger of fuel theft and fraud during distribution. Biodiesel adoption requires investment in storage facilities, gas station renovations, and transport infrastructure to increase its distribution network.

2.3.6. Cost and economic viability

Economic viability is another biodiesel factor. Due to higher feedstock and process costs, production costs for this diesel are more significant than for standard diesel. Biodiesel feedstock costs are unpredictable, with soybean oil prices fluctuating 20 % year-over-year [257]. A full-scale biodiesel plant costs over $50 million, making it difficult for new manufacturers to enter [258]. Large-scale production facilities are necessary to compete with petroleum diesel and obtain economies of scale [259]. Government incentives and economies of scale could lower these costs and boost market competition. Naylor et al. [260] estimated that a 5 % biodiesel subsidy cut might reduce production by 10 %. Influences on the worldwide biodiesel market include geopolitical events and international renewable energy policy. Market dynamics and technological advances are needed to make biodiesel economically viable. Omidvarborna et al. [261] estimated that biodiesel tariffs could raise prices by $0.15 per gallon.

2.3.7. Fuel quality and standards

Biodiesel's acceptability depends on fuel quality and requirements. ASTM D6751 and EN 14214 require biodiesel to meet certain requirements, including a minimum cetane number of 47, a maximum viscosity of 6.0 mm2/s at 40 °C, and oxidation stability with a 6-hour induction period [262]. High-quality fuel ensures engine performance and user confidence. Deviations in these characteristics can reduce fuel efficiency and violate regulatory standards. Biodiesel's chemical nature degrades rubber components, making compatibility with older engines a real issue. The fuel's higher cloud point, 3–12 °C over petrodiesel, might block filters in cold settings [263]. Testing, certification, and quality assurance maintain standards and prevent residue buildup and fuel system obstructions.

3. Nanofluids in IC engines

3.1. Role of nanofluids in improving engine efficiency and emissions

One of the most notable attributes exhibited by nanofluids is their capacity to considerably augment heat transfer in comparison to conventional fluids. The primary cause of this property can be ascribed to the existence of nanoparticles, which possess a significantly high ratio of surface area to volume. Fig. 18 depicts the typical secondary atomization mechanism of fuels with nanomaterials. Nanoparticles may cause secondary atomization of fuel droplets [264]. The nanoparticles in the fuel's microscopic water droplets mix fuel and air, boosting combustion. Micro-explosion is caused by heterogeneous nucleation. Nucleation occurs mostly on the droplet surface. The nanoparticles engage in interactions with the underlying fluid, thereby modifying its thermal conductivity and convective heat transfer properties [265]. Nanoparticles in engine cooling systems allow nanofluids to absorb and dissipate heat, maintaining appropriate engine operating temperatures [266]. This is significant because engines that operate at elevated temperatures typically experience decreased efficiency and increased attrition, resulting in higher emissions and a shorter engine lifespan [267]. Nanofluids can reduce engine friction and wear, making them interesting. IC engines mechanical friction dissipates energy. Nanofluids use nanoparticles as lubricants to create a safe boundary layer between engine components. Friction reduction improves mechanical efficiency and engine smoothness. Also, because there is less contact, there is less wear and tear on the engine parts [268]. This results in an increased engine lifespan and lower maintenance costs.

The capacity of nanofluids to improve combustion efficiency is a significant advantage of incorporating them into engines. The reaction between fuel and air that takes place during the combustion process inside of an engine needs to take place in a prompt and controlled manner [269]. Nanoparticles in fuel or intake air can boost nanofluid catalytic capabilities, improving fuel–air mixture combustion. Optimizing combustion processes increases fuel economy, reducing unburnt hydrocarbons and other hazardous emissions [270]. Consequently, the use of nanofluids has the potential to mitigate the emission of harmful pollutants such as nitrogen oxides (NOx) and particulate matter, thereby contributing to efforts to reduce emissions. Nanofluids reduce pollutants and improve combustion efficiency. Nanoparticles contained in nanofluids can operate as catalysts, aiding a variety of chemical reactions and resulting in the reduction of harmful emissions [271]. They can quickly convert nitrogen oxides into less harmful molecules or nitrogen and oxygen gases. Agbulut [109] investigates the effect of nanoparticle size on the performance of a fuel injection (CI) engine. Titanium oxide nanoparticles of three different sizes were introduced to canola oil methyl ester-diesel blends, resulting in lower viscosity, heating value, and cetane number. The use of nanoparticles increased unit and specific exergy costs while improving energy and exergy efficiency. According to the study, nanoparticle-added fuels provide better exergy, energy, sustainability and thermoeconomic results as shown in Fig. 19.

Nanofluids offer a promising pathway to mitigate the environmental

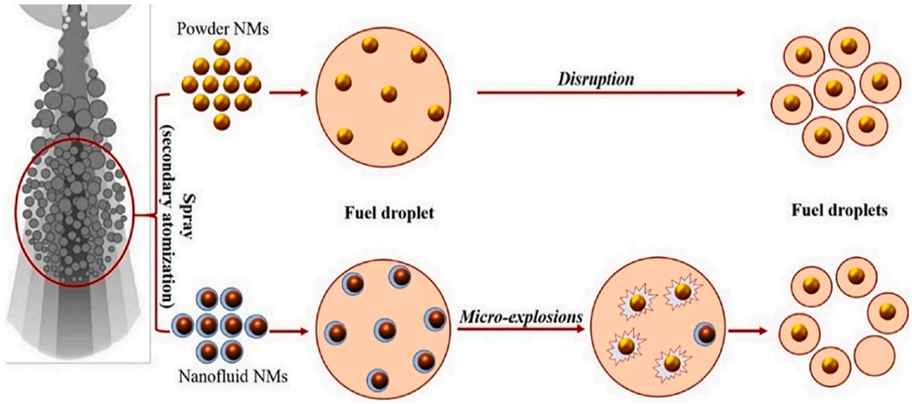

Fig. 18. Fuel secondary atomization mechanism [264] (Adapted with permission from Elsevier BV with License No.: 5723470300206).

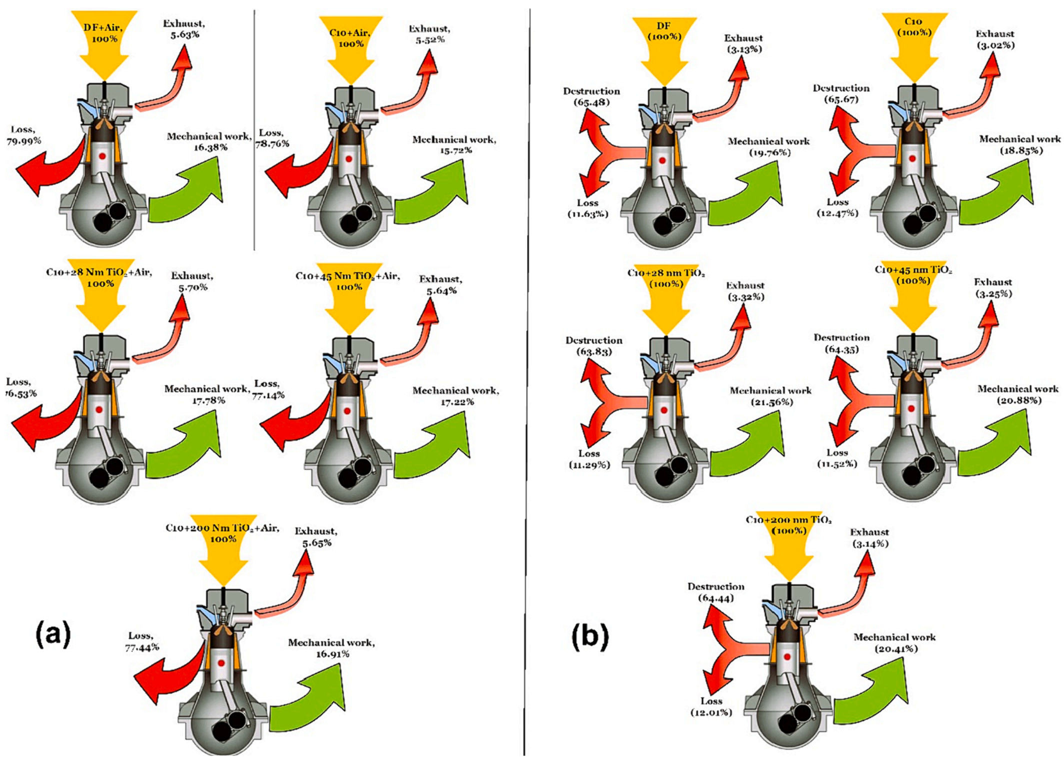

Fig. 19. Sankey diagram for energy balance and Grassman diagram for exergy balance. [109] (Adapted with permission from Elsevier BV with License No.: 5723470117908).

impact of IC engines by potentially oxidizing carbon monoxide and hydrocarbons, leading to cleaner exhaust emissions [272]. Integrating nanofluids into engine design holds significant promise for reducing emissions while enhancing engine performance. Additionally, nanofluids present opportunities for reducing the size of cooling systems [273]. Their superior heat transfer properties enable efficient heat dissipation from the engine, facilitating the development of more compact and lightweight cooling systems. Downsizing not only contributes to enhanced engine efficiency but also offers manufacturers greater flexibility in engine design, leading to improved vehicle aerodynamics and overall fuel efficiency [274].

Despite these numerous potential benefits, several obstacles require resolution before widespread adoption of nanofluids in the automotive sector. One primary challenge lies in the long-term stability and dispersion of nanoparticles within the base fluid [275]. Nanoparticle aggregation can negatively impact the overall efficacy of nanofluids over time. Therefore, thorough research into stable and enduring nanofluid formulations is crucial to preserve their advantageous properties during engine operation [276]. Furthermore, cost-effectiveness and scalability of nanofluid production must be carefully considered [277]. Due to their high cost, industrial-scale manufacturing is necessary for integrating nanofluids into mass-produced vehicles. While nanofluids have the potential to improve both IC engine efficiency and emissions reduction [278], their unique thermal properties and possible catalytic abilities present the automotive industry with exciting new avenues for addressing critical challenges. However, overcoming the hurdles associated with long-term stability, scalability, and cost-effectiveness necessitates further research and development efforts. By persistently advancing nanofluid technologies, the automotive sector has the potential to pave the way for transportation solutions characterized by enhanced efficiency, environmental friendliness, and long-term sustainability.

3.2. Types of nanoparticles used in nanofluids for IC engines

Nanofluids employed in internal combustion engines (IC engines) are comprised of nanoparticles that are dispersed within a base fluid [279]. Nanomaterials are particles smaller than one micrometer. They are categorized as inorganic or organic nanoparticles. Fig. 20 provides a clear illustration that highlights the additional categorization of organic and inorganic nanoparticles. The utilization of nanoparticles is of paramount importance in augmenting heat transfer, optimizing combustion efficiency, and mitigating friction and wear in various engine components [280]. Various types of nanoparticles have been examined for their potential application in nanofluids designed for IC engines. Several nanoparticles are frequently examined in research studies.

3.2.1. Metal oxides

Metal oxide nanoparticles have received considerable interest as potential candidates for incorporation into nanofluids designed for utilization in IC engines [282]. Nanoscale metal oxides of the types CeO_2, Al_2O_3, MgO, CuO, TiO_2, ZnO, ZrO_2, and others are added to fuel in the form of additives in order to encourage complete combustion [283,284]. Nanoparticles made of metal oxide are favored for use in nanofluid applications due to their thermal stability. In an IC engine, nanoparticles must maintain stability and avoid any chemical or physical changes affecting their performance [285]. Metal oxides are stable and appropriate for engine operation. It is also essential to note that metal oxide nanoparticles have extreme thermal conductivity. This attribute is fundamental in enhancing nanofluids' heat transport. Therefore it is crucial to be aware of this fact. Through thermal transfer, nanofluids can enhance engine performance [286]. Metal oxide nanoparticles improve the base fluid's thermal conductivity. Nanofluids improve the engine's ability to absorb, convey, and dissipate heat, increasing cooling efficiency and reducing the risk of engine overheating [287].

Due to its redox characteristics, cerium dioxide (CeO_2) nanoparticles can store and release oxygen, making them popular fuel additives [288,289]. High temperatures and a reducing environment generate oxygen-deficient, non-stoichiometric oxides (CeO_2-x). However, in an oxidizing atmosphere, CeO_2-x oxides quickly return to CeO_2 [290,291]. The Ce3+/Ce4 + redox pair drives this reversible mechanism. CeO_2 nanoparticle lattice oxygen vacancies result from Ce4 + to Ce3 + reduction [292]. Notably, the nanoparticle crystal structure remains intact despite these vacancies. CeO_2's oxidation and reduction abilities help reduce hazardous emissions [293,294]. It reduces nitrogen oxides by absorbing oxygen and oxidizing carbon monoxide (CO) and hydrocarbons (HC). CeO_2 helps oxidize hydrocarbons and soot. The oxygen-supplying mechanism of CeO_2 helps reduce the emissions of UHC, CO, and soot [295,296].

Metal oxide nanoparticles' catalytic capabilities are another benefit. Nanoparticles can speed up the burning process in an engine cylinder [297]. Fuel and air combustion affects an engine's performance and emissions. Therefore, one of the most critical aspects that determines an engine's performance and emissions is the efficiency with which the engine burns gasoline. Saravankumar et al. [298] added 35 nm SiO_2 nanoparticles to biodiesel-diesel mixes in another investigation. These nanoparticles increase fuel cetane number, enhancing combustion and raising chamber temperatures. This shortens fuel delay and improves ignition. Due to greater combustion temperatures, NOx and CO_2 emissions increased. SiO_2 reduced CO, HC, and smoke emissions in fuel mixes compared to those without nanoparticles. Metal oxide nanoparticles may increase combustion efficiency and completeness, reducing emissions. Nanoparticles of metal oxide accelerate the decomposition of complex hydrocarbons and the oxidation of CO and HC, resulting in the production of less hazardous substances [299]. Thus, less NOx and particulate matter, which cause air pollution and harm the ecosystem, are discharged. Metal oxide nanofluids have the potential to improve the performance of engines by increasing the efficiency of combustion and lowering emissions. As a result, these nanofluids are safe for the environment and sustainable [300]. Mahalingam and Ganesan [301] found that biodiesel-diesel blends with lower nano additives function better and emit less. They added 25–30 nm nano Al_2O_3 to biodiesel-diesel blends at 10, 15, and 20 ppm concentrations. The 10 ppm nano additive concentration had superior Brake Thermal Efficiency (BTE), lower Brake Specific Fuel Consumption (BSFC), and lower exhaust emissions

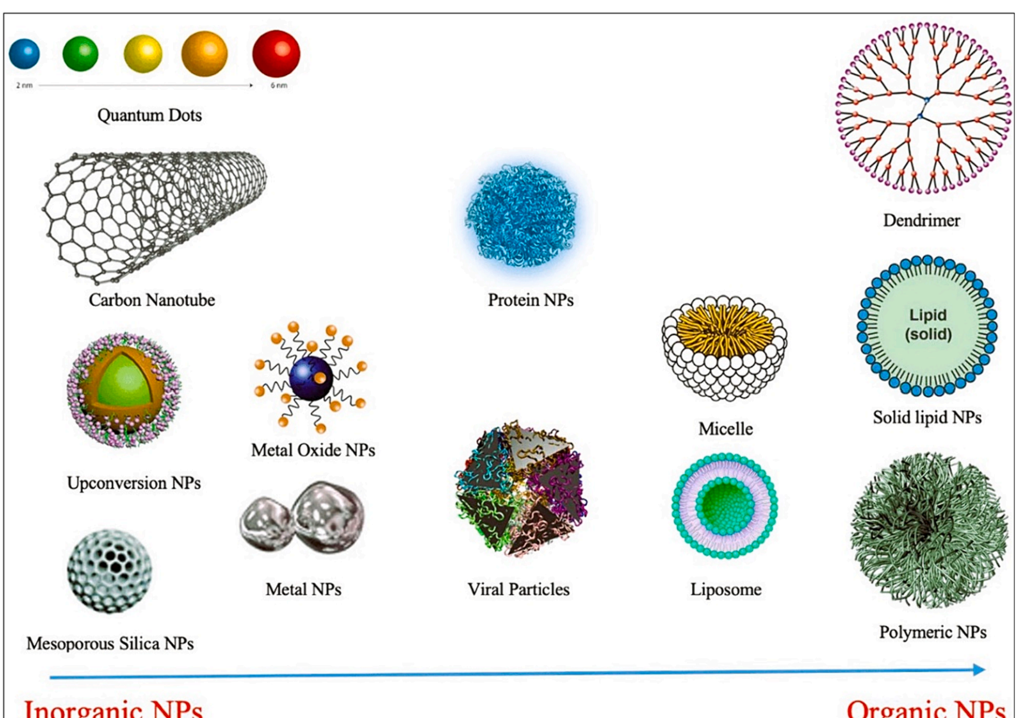

Fig. 20. Nanoparticles classification [281]

than 15 and 20 ppm. Increasing the concentration of nano additives resulted in higher viscosity and density of the fuel mixture, but at the same time, it decreased the calorific value. The mitigation of detrimental pollutants holds significant significance in tackling worldwide environmental issues, including air quality and climate change. Nano-additives' exhaust emission-controlling efficiency depends on nanoparticle size [302]. To investigate this, a study added 100 ppm of 10 and 20 nm SiO_2 nanoparticles to diesel fuel. This study found that 20-nm SiO_2 nanoparticles reduced exhaust pollutants more than 10-nm ones. The fuel with 20 nm nano additives had a higher calorific value than that with 10 nm. Trials using 20 nm AgO nano additives in biodiesel had superior performance and lower emissions than 10 nm nanoparticles [303]. The link between fuel nanoparticle concentration and performance and emissions is complicated. Nanoparticle concentration increases improve performance and reduce emissions, but exceeding a threshold can result in decreased performance and increased emissions [304]. High nanoparticle concentrations change fuel density, viscosity, flash point, calorific value, fire point, and cetane number. Alterations in the properties of fuel can have a detrimental effect on a system's efficiency and the amount of emissions it produces [305].

In particular, increasing the concentration of nanoparticles can alter combustion by increasing density, flash point, and fire point. Excess nanoparticles can increase engine banging and instability. Reduced calorific value, increased viscosity, lower cetane number, and higher fuel flash and fire points are the reasons for these changes [306]. Nanoparticles can improve fuel performance and emissions, but their concentration must be carefully considered to avoid side effects.

3.2.2. Metal nanoparticles

Noble metal nanoparticles, such as gold (Au), silver (Ag), and copper (Cu), have gained significant attention as promising candidates for the advancement of nanofluids in the context of IC engines [307]. The nanoparticles have garnered significant interest owing to their remarkable thermal conductivity and unique surface properties, which have the potential to exert a positive impact on the combustion process within the engine [308]. The exceptional thermal conductivity exhibited by noble metal nanoparticles is a prominent characteristic that contributes to their desirability in nanofluids. Thermal conductivity is a fundamental property that quantifies the capacity of a material to conduct heat, and noble metals demonstrate exceptional performance in this aspect [309]. The inclusion of noble metal nanoparticles in the base fluid leads to a substantial improvement in the overall heat transfer efficiency of the nanofluid. The aforementioned characteristic assumes a crucial function in IC engines, where efficient thermal regulation is of utmost importance to guarantee optimal engine operation and mitigate the risk of excessive heat buildup.

Numerous people must be aware that a stream of explosive metal granules with particle sizes of less than 20 μm can maintain flames when suspended inside air with adequate concentrations of metal [310]. Fig. 21 depicts metal-based fuel flames supported by Bunsen burner juxtaposed having methane-air flame commonly observed in chemistry laboratory. This burner propels particulate in the range of 1–20 μm inside the air stream or further oxidising fumes [311,312]. As the metal-fuel mixture emanates from a burner, the flame is maintained by the heat dissipating towards a burner's edge [313,314], as depicted in Fig. 22. In the 1960 s, Cassell was the first to stabilize these laminar metal-powder flames [315]. McGill [316,317] and other researchers [314,318,319] recently conducted in-depth examinations of previously neglected subjects.

The significance of noble metal nanoparticles is heightened as the fuel–air mixture undergoes ignition and combustion within the combustion chamber of the engine [320]. The nanoparticles exhibit distinct surface characteristics that function as catalysts in the process of combustion [321]. Catalysis entails the facilitation of chemical reactions without undergoing consumption or alteration during the course of the reaction. In the realm of IC engines, the inclusion of noble metal nanoparticles has a discernible impact on the kinetics of combustion, resulting in enhanced efficiency and regulated fuel combustion [322]. Enhancement of combustion efficiency by noble metal nanoparticles primarily occurs via improved fuel oxidation. The oxidation of fuel molecules is expedited by noble metal nanoparticles during the combustion process of the fuel and air mixture [323]. This phenomenon leads to enhanced combustion efficiency, whereby a greater proportion of the fuel undergoes conversion into productive work, generating energy to propel the engine, as opposed to being dissipated as unreacted

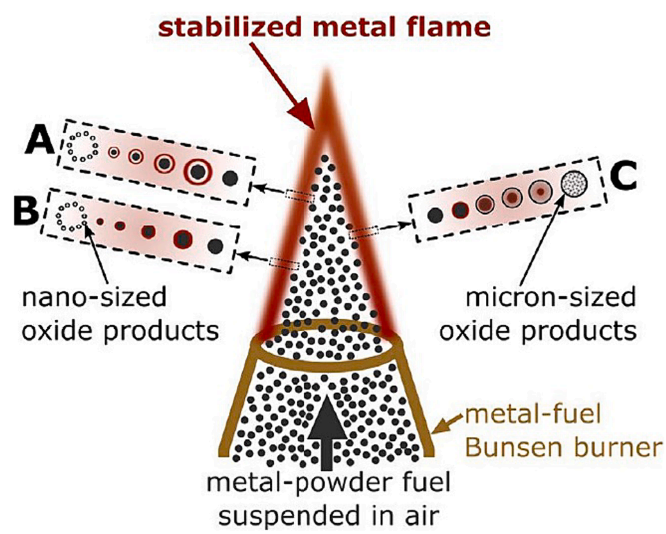

Fig. 22. McGill metal-fuel Bunsen burner sketch of stabilised metal–air flame [314] (Adapted with permission from Elsevier BV with License No.: 5723461353453).

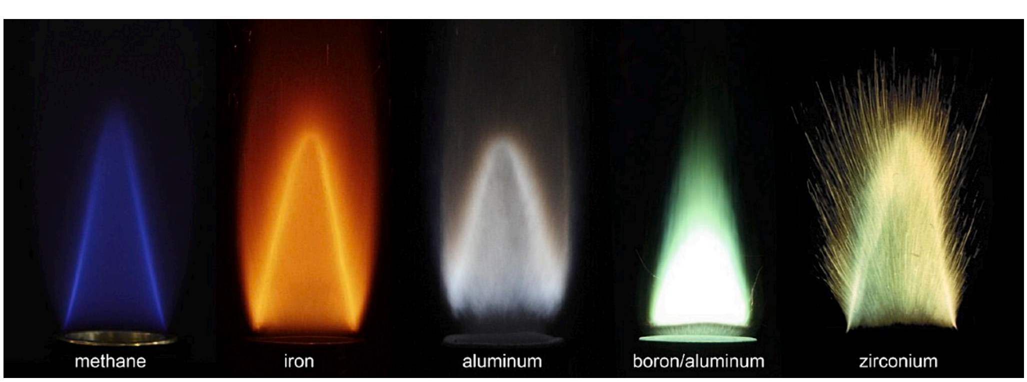

Fig. 21. Air-stabilized metal fuel flames vs. methane–air flames [314] (Adapted with permission from Elsevier BV with License No.: 5723461353453).

hydrocarbons [324].

Saraee et al. [325] added silver nanoparticles to fuel for diesel engines. Silver nanoparticles increased fuel heat transmission and decreased ignition delay. The combustion properties were enhanced, reducing emissions significantly. CO and NOx emissions dropped 20.50 % and 13 %, respectively. The results showed a 3 % fuel consumption reduction and a 6 % engine power increase. Tanvir and Qiao [326] observed that 5 wt% aluminium nanoparticle in ethanol increased burning rate by 140 %. High nanoparticle radiation absorption from the flame to the droplets for vaporisation increased burning rate. Allen et al. [327] found that 2 wt% aluminium nanoparticles in ethanol reduced igniting delay by 32 %. Increased droplet thermal conductivity reduced ignition delay, they said. Nanoparticle-added fuel might ignite earlier due to improved heat transfer.

Moreover, the catalytic properties exhibited by noble metal nanoparticles also encompass the capability to mitigate the levels of detrimental emissions present in engine exhaust [328]. During the process of combustion, the emission of hydrocarbons and various other pollutants occurs as byproducts [329]. Noble metal nanoparticles have the ability to mitigate the generation of detrimental emissions by facilitating complete combustion. Furthermore, they possess the capability to facilitate the conversion of nitrogen oxides (NOx) into nitrogen and oxygen gases, which are comparatively less detrimental. The catalytic activity of noble metal nanoparticles plays a crucial role in effectively reducing emissions, thereby making a substantial contribution towards mitigating the environmental consequences associated with IC engines [330].

Debbarma and Misra [331] injected 50 ppm iron nanoparticles under 25 nm to diesel–biodiesel combination. Nanoparticles improve fuel blend viscosity, density, and calorific value. Metallic particle and conventional fuel oxidation heat [332]. Jones et al. [333] added 1–10 % 50-nm aluminium nanoparticles to ethanol fuel. They observed that nanoparticle concentration linearly enhances fuel combustion heat. Up to 3 % concentration, heat of combustion is enhanced but not significantly. HC, CO, and NOx emissions dropped 6 %, 12 %, and 11 %. Nanoparticle-laden fuel's increased thermal conductivity and calorific value improved performance and reduced emissions. Higher calorific value lowers fuel usage, and smaller ignition delay improves combustion. Kumar et al. [334] added 0.25, 0.5, and 0.75 wt% silicon nanoparticles to diesel fuel. Si 0.5 fuel has improved combustion chamber pressure and heat release, according to combustion studies. Si 0.5 gasoline generates 8.95 % more BTE and 5.91 % more torque than diesel. Compared to diesel, Si 0.5 fuel emits 28.57 % less CO, 27.3 % less NOx, and 20.63 % more HC.

Given the growing urgency of air pollution and climate change, the utilization of nanofluids incorporating noble metal nanoparticles presents a viable approach to mitigate the environmental impact of IC engines and foster the adoption of more environmentally friendly transportation alternatives [335]. Nevertheless, the incorporation of noble metal nanoparticles into nanofluids for IC engines presents several challenges. One of the foremost considerations revolves around the attainment and sustenance of a stable dispersion of these nanoparticles within the underlying fluid medium. The agglomeration or settling of nanoparticles has the potential to impact their catalytic activity and overall performance [336]. Consequently, scientists are currently engaged in the exploration of novel methodologies aimed at achieving a consistent dispersion of nanoparticles and mitigating their degradation during prolonged engine usage.

3.2.3. Carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) are a remarkable category of nanomaterials characterized by their distinctive cylindrical structure, which consists of carbon atoms organized in a tubular configuration [337]. CNTs are one-dimensional carbon materials with unique shape and chemical properties [338,339]. SWCNTs and MWCNTs, cylindrical carbon structures, have different configurations that affect their characteristics and uses. As fuel additives, CNTs have several benefits [340]. CNTs have very good thermal conductivity and mechanical strength. This makes them very desirable for possible improvements in heat transfer and less noise in IC engines. CNTs improved fuel combustion and heat transmission [341,342]. These materials transfer heat better than copper and diamond. It was claimed that CNTs fill fuel intermolecular gaps, making slipping easier and reducing viscosity. This viscosity reduction improves fuel atomisation [342]. Trapping free radicals makes CNTs an anti-knock additive. This makes carbon nanotubes (CNTs) ideal for nanofluid heat transfer. Nanofluids' thermal conductivity is increased by dispersing carbon nanotubes (CNTs) in the base fluid. In the world of IC engines, keeping the engine running at the right temperature depends on how well heat is transferred. Overheating can reduce engine performance, mechanical damage, and malfunction, thus heat must be dissipated efficiently. Diesel fuel with CNTs has higher cetane numbers. CNTs' excellent thermal conductivity accelerates fuel combustion heat transfer. CNTs accelerate burning, clean burning, and smoke reduction [112].

In addition to their remarkable thermal properties, CNTs also have extraordinary mechanical strength. The CNTs have a very high tensile strength, which means they can handle a lot of mechanical stress without breaking or deforming [343]. This trait reduces engine friction and wear. Literature shows that CNTs as fuel additives improve performance and reduce exhaust pollutants. CNTs mixed with diesohol (Ethanol + Diesel) enhanced BTE and torque by 13.97 % and 15.52 % over pure diesel. HC and CO emissions dropped 31.72 % and 5.47 %, respectively. However, NOx emissions rose 12.22 %. The presence of CNT facilitated complete combustion, which reduced exhaust pollutants [114]. Compared to neat biodiesel, 100 ppm CNT reduced smoke, CO, HC, and NOx, emissions by 7.8 %, 5.9 %, 6.7 %, and 9.2 %. However, CO_2 emissions rose 7.9 %. CNTs increased thermal conductivity and cetane number, reducing exhaust emissions. CNTs in biodiesel improved heat transfer and catalytic activity, increasing CO_2 emissions [339]. Chen et al. [344] examine diesel fuel additives Al_2O_3, SiO_2, and CNT for performance and emissions. Due to its higher calorific content, CNT-blended fuel improved BSFC by 19.85 %. Due to lower ignition delay, BTE improved 18.80 % over diesel. NOx exhaust emissions dropped 4.48 %, however HC, CO_2, and CO increased. CNTs in lubricating oil form a protective boundary layer between engine components. Because of the interaction and movement of engine parts, frictional forces are generated. These forces lead to the loss of energy and an accelerated deterioration of the components of the engine. CNT-based nanofluids as lubricants incorporate CNTs as tiny reinforcements, reducing engine component contact and friction. Friction reduction improves mechanical efficiency, engine lifespan, and maintenance costs.

MWCNT also greatly decreases emissions. The study indicated that adding MWCNT to biodiesel–diesel mixture reduced HC, CO, and NOx emissions by 60 %, 50 %, and 35 %. MWCNT reduces ignition delay and accelerates combustion, reducing emissions [345]. Adding graphene oxide nanoparticles to diesel–biodiesel mixes reduces emissions. HC and CO emissions decreased by 15–28 % and 7–20 %, respectively, compared to unmixed biodiesel. NOx and CO_2 emissions rise 5–8 %, and 6–10 % respectively. Graphene oxide nanoparticles increased chemical reactivity, reducing ignition delay and improving combustion [346].

Carbon nanotubes in the nanofluid lubricant boost its durability and resilience [347]. Even in difficult operational conditions, a consistent level of lubrication performance may be maintained because to the ability of CNTs, to withstand high levels of mechanical stress as well as temperatures [348]. Carbon nanotubes can improve heat conductivity and mechanical characteristics, improving the efficiency and performance of IC engines. The advancement of research and development in nanofluid technology has the potential to significantly enhance engine cooling and lubrication through the optimization of carbon nanotube-based nanofluids [349]. This, in turn, could result in the development of transportation solutions that are more efficient and sustainable. Nevertheless, there are still unresolved issues pertaining to the stable dispersion of carbon nanotubes in the base fluid and the ability to scale up their production. Achieving a homogeneous dispersion of carbon nanotubes within the nanofluid is of utmost importance in order to effectively exploit their advantageous properties [350]. Furthermore, the establishment of economically viable and high-capacity production methods for carbon nanotube-based nanofluids will be imperative to facilitate their extensive integration within the automotive sector.

3.2.4. Graphene nanoplatelets

Graphene nanoplatelets (GNPs) have emerged as a captivating category of nanomaterials that has garnered significant interest in contemporary times [351]. The carbon atoms in this arrangement form a hexagonal lattice, resulting in the formation of two-dimensional sheets [351]. Thermal conductivity and mechanical strength make graphene nanoplates excellent for nanofluids in IC engines. GNPs have exceptional thermal conductivity. Even though GNPs are thin, they are better at letting heat through than other materials [352]. GNPs' high thermal conductivity makes them ideal for cooling engine nanofluids. Well-cooled IC engines don't overheat. GNP-dispersed nanofluids boost thermal conductivity. Nanofluid thermal conductivity allows for better heat absorption and disposal. This maintains essential engine component temperature limits. Because of this, the engine is able to function at a higher efficiency, which in turn reduces the potential for damage caused by heat.

GNPs are good nanofluids for IC engines due to their mechanical strength. Friction and wear caused by engine components moving and contacting one other over time degrade and lose energy [353]. But adding graphene nanoparticles to the base fluid as nanofluids could help reduce these side effects. In the nanofluid GNPs form a protective boundary layer that isolates and protects engine moving parts. The presence of a boundary layer efficiently mitigates direct contact and friction between components, resulting in lower wear rates and less energy waste due to friction [354]. Therefore, the utilization of GNPs in nanofluids has the potential to enhance mechanical efficiency, prolong the operational lifespan of engines, and mitigate the necessity for frequent maintenance and replacement of components.

Furthermore, the integration of graphene nanoplatelets can offer supplementary advantages in engine design and operation due to their augmented thermal conductivity and mechanical robustness [355]. Enhanced heat transfer and diminished friction may provide engine designers with increased latitude to optimize the dimensions, mass, and overall efficacy of the engine. These phenomena may lead to smaller and lighter engine cooling and lubrication systems, which would increase fuel economy and vehicle performance. GNPs have many applications, but they can only be fully used if they are uniformly disseminated in a fluid media [356]. It is of the utmost importance to ensure that a homogenous dispersion of GNPs is maintained inside the nanofluid in order to keep the functioning consistent and reliable in actual engine implementations [357].

3.2.5. Hybrid nanoparticles

Researchers have explored the utilization of hybrid nanoparticles in the optimization of nanofluids for IC engines, aiming to enhance engine performance through an innovative and distinct approach. Hybrid nanoparticles are synthesized through the amalgamation of diverse materials, typically possessing unique characteristics, in order to fabricate a nanoscale architecture that maximizes the advantageous qualities of each constituent [358]. An exemplary illustration of hybrid nanoparticles involves the amalgamation of a core composed of metal oxide with a shell made of metal. The design in question exhibits ingenuity by producing a particle at the nanoscale level, featuring a core composed of metal oxide that is enveloped by a metal shell. The core–shell architecture facilitates the synergistic exploitation of the properties inherent in both materials. The metal oxide core is frequently chosen due to its exceptional thermal stability and elevated thermal conductivity [359]. The inclusion of the metal oxide core in the nanofluid enhances its heat transfer properties [360]. The generation of heat during engine operation results in the efficient conduction and dissipation of heat throughout the nanofluid, facilitated by the metal oxide core. This process contributes to the maintenance of optimal engine operating temperatures.

Conversely, the incorporation of a metal shell in the hybrid nanoparticle confers supplementary advantages, such as catalytic properties [361]. Metals, particularly noble metals such as gold (Au), silver (Ag), and platinum (Pt), are widely recognized for their exceptional catalytic characteristics. The metallic enclosure functions as a catalyst during the process of combustion, effectively facilitating and expediting the chemical reactions associated with the oxidation of fuel [362]. The combustion process within the engine's combustion chamber is enhanced by the catalytic metal shell, resulting in increased combustion efficiency through the promotion of more thorough fuel combustion. An enhanced combustion process leads to a decrease in the production of unburnt hydrocarbons and other detrimental pollutants, thereby resulting in reduced emissions and the generation of cleaner exhaust gases [363].

In addition, the presence of the metal shell serves to enhance the overall stability and durability of the hybrid nanoparticle within the nanofluid [364]. The presence of a metal shell serves the purpose of safeguarding the metal oxide core against possible agglomeration or degradation, thereby ensuring the preservation of the nanofluid's enhanced properties throughout prolonged engine operation. Through the strategic utilization of the inherent advantages possessed by both materials, hybrid nanoparticles present a versatile and multifaceted approach to augmenting engine efficiency while concurrently mitigating emissions [365]. The synergistic effect resulting from the combination of enhanced heat transfer facilitated by the metal oxide core and improved combustion efficiency achieved through the catalytic metal shell contributes significantly to the enhancement of IC engines performance. The inherent adaptability of hybrid nanoparticles enables the exploration of diverse material combinations and structural arrangements, thereby presenting avenues for additional customization and refinement. Scientists are currently engaged in ongoing investigations into innovative hybrid nanoparticle configurations, which involve the integration of various materials, structures, and compositions to meet specific engine specifications. However, there are still obstacles to surmount in the synthesis and manufacturing processes of hybrid nanoparticles. To achieve reliable functioning, their size, composition, and dispersion in the base fluid must be precisely controlled. Hybrid nanoparticles in nanofluids for internal combustion (IC) engines have promising benefits, and current research is focused on fully using them to advance engine technology. Table 5 displays potential enhancements in performance of engine with the addition of nanoparticles into pure oil.

3.3. Challenges and considerations in nanofluid in biodiesel

While the integration of nanoparticles with biodiesel offers promising advantages, several challenges impede its widespread adoption and require careful consideration:

1. Nanoparticle selection and Design:
   - Identifying the optimal type: Choosing the most suitable nanoparticle material, size, shape, and surface functionalization is crucial. Inappropriate selection can lead to unintended consequences, including:
     - o Negative impact on fuel properties: Nanoparticles might adversely affect stability, viscosity, or cetane number if not chosen carefully.
     - o Engine wear and tear: Incompatible nanoparticles could increase wear on engine components or promote deposit formation.
2. Production Challenges:

Table 5
Potential enhancements in performance of engine nanoparticles

Nanoparticles	Simple/ Hybrid	Base oil	Outcome	Refs
Al_2O_3/TiO_2	Hybrid nanofluid	5 W-30	Improvement in heat transmission by 9 % 14 %	[366]
Al_2O_3, TiO_2	Simple nanofluid	5 W-30	Part investigated: piston ringAl_2O_3 impact: 29 % lower abrasion rateTiO_2 reduces ablation by 21 %	[367]
Al_2O_3, SiO_2	Hybrid nanofluid	SAE15W40	At low volume fractions, wear reduced and engine efficiency increased. Al_2O_3 reduced BSFC. Frictional power was lowered by Al_2O_3. Al_2O_3 outperformed SiO_2 nanoparticles.	[368]
Al_2O_3/TiO_2	Hybrid nanofluid	5 W30	fuel saving upto 16 % 20 %	[369]
Cu TiO_2	Simple nanofluid	SAE 20 W40	BSFC enhancement reduces fuel consumption to generated power.	[370]
Gr	Simple nanofluid	5 W30	Optimized engine power by 7 %-10 % Reduces exhaust emissions by 3 %-5% and saved 17 % gasoline.	[371]
MoS_2	Simple nanofluid	SAE 5 W30	Optimise fuel consumptionNOx reduction benefitsCO_2 reduction benefits	[372]
MoS_2	Simple nanofluid	5 W-30	Reduce emissions or pollution	[373]
MoS_2	Simple nanofluid	Zinc-free 5 W30	Fuel consumption dropped 0.9 %	[372]
MoS_2	Simple nanofluid	Polyalphaolefin 4 (PAO)	40 %–50 % torque reduction	[374]

- Integration into existing processes: Efficient and scalable methods for incorporating nanoparticles into the biodiesel production process are needed without disrupting existing infrastructure.
- Dispersion difficulties: Ensuring uniform and stable dispersion of nanoparticles within the biodiesel is essential to avoid agglomeration and achieve desired effects.
- Cost considerations: The cost of nanoparticle production and its impact on the overall economic viability of the biofuel production process needs careful evaluation.

3. Environmental and sustainability Concerns:
- Potential environmental risks: The potential environmental impact of nanoparticle production, use, and disposal throughout the lifecycle needs thorough assessment. This includes potential risks associated with nanoparticle release into the environment and potential ecotoxicity.
- Sustainability considerations: The overall sustainability of the process, including energy consumption and potential resource depletion associated with nanoparticle production, needs to be evaluated alongside the potential benefits for biodiesel production.

4. Long-Term engine Effects:
- Limited understanding of long-term impacts: The long-term effects of nanoparticle-infused biodiesel on engine components, lubrication performance, and potential deposit formation require comprehensive investigation.
- Uncertainty about potential risks: The potential for unforeseen negative consequences on engine performance, emissions, or durability needs ongoing research and monitoring.

5. Knowledge gaps and regulatory Landscape:
- Limited data on specific nanoparticle-biodiesel combinations: A comprehensive understanding of the interaction between various nanoparticles and biodiesel, and their combined effects, is still under development.
- Evolving regulatory landscape: Regulations governing the use of nanomaterials in fuels are still evolving, requiring careful navigation and compliance considerations.

Addressing these challenges is crucial for the responsible and sustainable development of nanoparticle-infused biodiesel. Continued research and development efforts are essential to optimize nanoparticle selection, production processes, and mitigate potential environmental and engine-related risks. Only through comprehensive evaluation and responsible implementation can the true potential of nanoparticle-enhanced biodiesel be realized.

4. Nanofluid infused biodiesel combustion

Blending biodiesel with nanofluids offers a promising avenue to enhance fuel characteristics and optimize engine performance. These blends possess the ability to improve crucial properties such as thermal conductivity, viscosity, and specific heat capacity. However, ensuring the stability of nanoparticles within the biodiesel typically requires the inclusion of surfactants or other stabilizing agents, potentially impacting the fuel's overall integrity and combustion properties, thereby adding complexity. Within the domain of engine performance, measurements like brake specific fuel consumption (BSFC), brake horsepower (BHP), and thermal efficiency serve as fundamental benchmarks.

Understanding the emission profile of these blends is crucial, especially considering biodiesel's inherent lower emissions compared to conventional diesel. Close attention must be paid to key pollutants like particulates, carbon dioxide, carbon monoxide, and nitrogen oxides (NOx).

4.1. Effects of nanofluid additives on biodiesel properties

The dispersion of nanoparticles in biodiesel has the potential to induce interactions with the fuel molecules, hence modifying the physicochemical properties of the biodiesel. Numerous categories of nanoparticles, including metal oxides, carbon nanotubes, and nanoclays, have been extensively studied in order to explore their potential in augmenting the qualities of biodiesel.

4.1.1. Impact on thermal stability

The widespread adoption of biodiesel hinges on its **thermal stability** throughout its life cycle, encompassing production, storage, transportation, and ultimately, combustion. Biodiesel, derived from renewable sources, exhibits susceptibility to undesirable chemical transformations at elevated temperatures commonly encountered during storage and transportation. These transformations manifested as increased viscosity, polymerization, and the formation of degradation products, can lead to detrimental engine malfunctions [375,376]. Despite their diminutive size, nanoparticles exert an outsized influence due to their exceptionally high surface area-to-volume ratio, which significantly amplifies their reactivity and potential for interaction with surrounding molecules [377]. In the context of biodiesel, nanoparticle catalysts, renowned for their ability to accelerate chemical reactions without being consumed themselves, present a promising avenue for enhancing the fuel's thermal stability by stabilizing its molecular structure [378].

These nanoparticles act as thermal protectors for biodiesel, safeguarding it from degradation and preserving its quality by inhibiting polymerization, thereby maintaining fluidity and preventing filter clogging [405,406]. By incorporating nanofluid additives, the thermal stability of biodiesel is demonstrably enhanced, translating to extended shelf life and preservation of quality even at elevated temperatures. These advancements effectively address the challenges associated with storage and handling, paving the way for improved performance of biodiesel as a viable alternative fuel [407,408]. By harnessing the power of nanoparticle-mediated stabilization, the viability and widespread acceptance of biodiesel as a potent and sustainable energy source are significantly bolstered. This approach has the potential to address critical challenges in the realm of green energy and sustainable transportation, ultimately paving the way for the proliferation of readily available clean fuel options [409,410].

4.1.2. Viscosity modification

The environmental merits of biodiesel are overshadowed by its comparatively elevated viscosity in relation to conventional diesel fuel [379]. This viscosity difference causes operational issues such as injector jams and inadequate atomization during combustion. These drawbacks nullify biodiesel's benefits by lowering engine performance, increasing fuel economy, and increasing emissions [380]. Nanoparticles are small entities with significant potential to revolutionise the properties of biodiesel. The extraordinary surface area-to-volume ratio of nanoparticles gives them a unique ability to alter the properties of fluids [381].

Nanoparticles manipulate their lubricating power by deftly squeezing between biodiesel molecules, creating a more fluid and less viscous mixture [382]. The use of nanoparticles leads to a transformation in the flow dynamics of the fuel, resulting in improved ease of movement through fuel systems, lines, and injectors [383]. In addition, the increased fluidity achieved by the participation of nanoparticles sets off a chain reaction in the combustion process that confirms the fuel to be broken down into tiny droplets for effective and complete combustion. Biodiesel exhibits increased fuel–air mixing and combustion kinetics due to its reduced viscosity, forming smaller droplets. Combustion becomes more complete, leading to decreased emissions as a result [384]. Nanofluid additives can effectively address injector performance, atomization, and viscosity by utilizing the lubricating properties of nanoparticles [385]. Therefore, nanofluids have the potential to enhance the operational efficiency and emissions of biodiesel, making it more comparable to diesel fuel [283].

4.2. Mechanisms of Nanofluid-Infused biodiesel combustion

The combustion of nanofluid-infused biodiesel presents a compelling avenue for enhancing engine performance and reducing environmental impact. However, this technology relies on intricate mechanisms that influence combustion efficiency, emissions, and overall engine operation. This section delves into the fundamental aspects governing this process, highlighting key areas of research and their significance.

- **Nanoparticle Dispersion and Stability:** A critical aspect of nanofluid-infused biodiesel combustion is achieving and maintaining a uniform dispersion of nanoparticles within the fuel [386]. This stability ensures even distribution throughout the combustion process, preventing agglomeration that could impede fuel flow and hinder performance [264]. Uniform dispersion is paramount for maximizing heat transfer and promoting efficient combustion, ultimately contributing to increased engine output and reduced emissions.
- **Heat Transfer Enhancement:** The incorporation of nanoparticles into biodiesel significantly improves its thermal conductivity [387]. This enhanced heat transfer translates to improved heat absorption and dissipation during combustion, leading to more efficient fuel vaporization and a more complete burn [388]. Consequently, this mechanism contributes to increased engine efficiency and the extraction of maximum energy from the fuel.
- **Catalytic Effects of Nanoparticles:** Certain nanoparticles, particularly metal oxides and noble metals, exhibit catalytic properties that influence the course of combustion reactions [389]. These nanoparticles act as catalysts, facilitating the breakdown of biodiesel molecules and promoting a more complete combustion process. This translates to a reduction in emissions of harmful pollutants like unburned hydrocarbons and particulate matter, contributing to cleaner and more efficient engine operation.
- **Influence on Ignition Characteristics:** The presence of nanoparticles can influence the ignition characteristics of biodiesel by altering ignition delay and combustion duration [390]. By carefully controlling these parameters, engineers/researchers can optimize the timing of combustion, ensuring efficient fuel utilization and maximizing energy extraction. This fine-tuning process paves the way for improved engine performance and overall efficiency.
- **Combustion Kinetics Modification:** Nanoparticles play a crucial role in modifying combustion kinetics by affecting the rates and pathways of various reaction processes [391]. This influence allows for the fine-tuning of the entire combustion process, ultimately leading to improved engine performance and a reduction in harmful emissions. By understanding and manipulating these kinetic effects, researchers can unlock the full potential of nanofluid-infused biodiesel for sustainable and efficient engine operation.
- **Nanoparticle-Biodiesel Interaction at Molecular Levels:** A deeper understanding of the interactions between nanoparticles and biodiesel at the molecular level is essential for optimizing their combined effects during combustion [392]. By elucidating these intricate relationships, researchers can design nanoparticles tailored to achieve specific combustion improvements. This knowledge empowers the development of targeted strategies for maximizing the efficiency and environmental benefits of nanofluid-infused biodiesel.
- **Particle Oxidation and Reduction Reactions:** During combustion, nanoparticles may undergo oxidation or reduction reactions, impacting the overall combustion chemistry [393]. By carefully managing these reactions, researchers can exert greater control over emission profiles and tailor combustion processes for specific applications. This targeted approach holds immense potential for achieving stricter emission regulations and contributing to a cleaner environment.
- **Emission Reduction Mechanisms:** The incorporation of catalytic nanoparticles within the nanofluid can facilitate the oxidation of exhaust gases, leading to a significant reduction in harmful emissions like particulate matter. This mechanism plays a pivotal role in ensuring environmental sustainability and compliance with increasingly stringent emission regulations. By harnessing the catalytic properties of nanoparticles, researchers can pave the way for cleaner burning engines and a more sustainable future.
- **In-Cylinder Heat Release Patterns:** The use of nanofluid-infused biodiesel can alter the patterns of heat release within the engine cylinder, impacting the efficiency of energy conversion [394]. A comprehensive understanding of these altered heat release patterns is crucial for optimizing engine design and combustion strategies, ultimately leading to enhanced performance and improved fuel economy.
- **Influence on Flame Stability:** Nanoparticles can influence the characteristics of flame propagation, impacting the stability of the flame during combustion [395]. Stable flames contribute to smooth engine operation, reducing the likelihood of engine knock and improving overall reliability. By understanding the influence of nanoparticles on flame stability, researchers can develop strategies to ensure smooth and reliable engine operation.

In conclusion, the intricate mechanisms governing the combustion of nanofluid-infused biodiesel encompass a multitude of factors, including nanoparticle dispersion, heat transfer enhancement, catalytic effects, and molecular-level interactions. Continued research in this domain is critical for unlocking the full potential of this technology, paving the way for cleaner, more efficient, and sustainable engine operation.

4.3. Impact of biodiesel-nanofluid combustion on engine performance and emissions

The investigation of the effects of biodiesel-nanofluid combustion on engine performance is a crucial field of study with the potential to significantly transform the application of sustainable fuels. Nanoparticles exert a profound influence on the intricate dynamics of combustion in ICEs fueled by biodiesel. These minute particles act as catalysts, altering fuel–air interactions and ignition processes, with the potential to revolutionize energy extraction efficiency. Central to this impact is the optimization of fuel–air mixing, a cornerstone of efficient combustion. Nanoparticles, when incorporated into the fuel, induce controlled turbulence, promoting intimate contact between fuel molecules and oxygen. This enhanced mixing fosters two crucial outcomes: firstly, it ensures consistent combustion throughout the fuel–air mixture, and secondly, it facilitates simultaneous ignition across the blend when using nanofluid additives. Notably, the high compatibility of nanoparticles with the fuel medium fosters seamless integration, eliminating distinct fuel and air compartments. This orchestrated arrangement, where each fuel particle is surrounded by oxygen, resembles a harmonious symphony.

The well-coordinated homogenization of the fuel–air mixture translates to significant benefits for combustion effectiveness. Homogeneous ignition propagation across the mixture minimizes incomplete or delayed combustion, resulting in a highly efficient and consistent process. Consequently, unreacted fuel and energy losses are minimized. In essence, nanoparticles orchestrate a “ballet” of combustion, enhancing fuel–air mixing, promoting uniform ignition, and maximizing energy extraction from each fuel droplet, bringing theoretical energy conservation principles to life and advancing energy efficiency. Beyond efficiency gains, nanofluid-enhanced combustion offers the potential to reduce emissions of harmful pollutants like particulate matter and NOx by promoting more complete combustion. Furthermore, the intricate interactions between nanoparticles and biodiesel molecules during combustion influence ignition timing, flame stability, and combustion rate, ultimately impacting engine performance. Table 6 provides a comprehensive evaluation of engine parameters, including power output, torque, and thermal efficiency, provides valuable insights into the overall impact of nanofluid additives on engine behavior.

Combining nanoparticles and biodiesel involves an intricate interplay of chemical and physical mechanisms that substantially impact the fuel’s characteristics and combustion behavior. Nanoparticles interact with the biodiesel matrix via surface adsorption, hydrogen bonding, and electrostatic interactions on a molecular level. The rheological properties of the fuel, including surface tension and viscosity, are altered by these interactions, resulting in enhanced atomization and combustion efficiency. Furthermore, in their capacity as catalytic sites, nanoparticles facilitate the oxidation of fuel molecules, thereby encouraging a more comprehensive combustion process. Additionally, the fuel’s thermal conductivity and heat transfer properties are modified by the presence of nanoparticles, which improves energy conversion and decreases heat losses during combustion. In addition, the efficacy of fuel additives is significantly influenced by the dispersion and stability of nanoparticles among the biodiesel matrix components. Scientists can enhance the compatibility between BD and nanoparticles to improve fuel efficiency and ecological sustainability through a more comprehensive understanding of these fundamental mechanisms.

5. Overview of AI/ML applications in the automotive industry

AI and ML have become indispensable components within the automotive industry, significantly transforming various aspects of vehicle development, manufacturing, safety, and the overall driving encounter [430]. The diverse ways in which AI is transforming the automotive industry include advanced driver-assistance systems (ADAS), predictive maintenance, natural language processing (NLP) applications, enhanced infotainment, robust cybersecurity, and optimized supply chain management [431]. AI serves as the core driving force behind autonomous driving technology, empowering vehicles to analyze sensor data and make real-time decisions based on their surroundings. ML algorithms play a critical role in this process, continuously improving the driving capabilities of autonomous vehicles by integrating knowledge from past experiences and data [432]. This iterative learning process allows AI to refine its understanding of the environment and optimize its driving behavior.

This overview examines the various applications of AI and ML within this industry. AI and ML algorithms play a central role in autonomous driving, serving as the fundamental components of self-driving vehicles [433]. The data obtained from various sensors, including LiDAR, radar, cameras, and GPS, is carefully processed to facilitate navigation, object recognition, and real-time decision-making in the context of driving [434]. Moreover, AI empowers ADAS features like lane departure warning, adaptive cruise control, and automatic emergency braking by enabling real-time analysis of sensor data and making critical decisions to enhance driving safety. ML algorithms meticulously analyze sensor data and identify patterns, enabling them to anticipate potential risks, predict driver actions, and ultimately enhance driving safety [435]. This predictive capability allows ADAS systems to intervene proactively, preventing accidents and fostering a sense of security for drivers.

Predictive maintenance systems further leverage the power of AI and ML. By analyzing sensor data and historical maintenance records, these systems can predict component failures with remarkable accuracy. This proactive approach allows for targeted maintenance interventions, leading to optimal vehicle performance and minimal downtime [435] , [427]. The application of predictive maintenance techniques is also applicable to the manufacturing process, ensuring timely servicing of machinery utilized in production to prevent breakdowns [436].

In manufacturing and quality control, implementing AI-powered robotics and automation systems has proven to be instrumental in optimizing production processes, resulting in improved efficiency and decreased errors [437]. Machine vision systems are of utmost importance in inspecting components ensuring the production of products of superior quality [438]. Furthermore, ML models significantly optimize supply chain logistics, resulting in cost reduction and lead time improvement. This is particularly vital within the intricate automotive manufacturing ecosystem.

AI-powered NLP systems understand and respond to natural language commands, enabling seamless interaction with infotainment systems and vehicle controls through voice commands, improving user experience and reducing distraction [439]. ML algorithms enhance the precision of speech recognition through iterative learning from user behavior and data. AI-driven infotainment systems could provide tailored content, suggestions, and voice identification for in-vehicle amusement. Incorporating virtual assistants such as Amazon’s Alexa and Google Assistant into automobiles allows drivers to operate a range of functions without requiring manual interaction, enhancing the overall driving encounter [440]. NLP is utilized to develop AI chatbots and voice recognition systems, enabling seamless communication in natural language between drivers and their vehicles. These systems support various tasks, including navigation, phone calls, and music selection, improving convenience and safety [441].

In traffic management and navigation, AI is utilized to examine real-time traffic data to offer dynamic routing alternatives, thereby alleviating congestion [442]. ML algorithms improve the precision of GPS systems and provide real-time traffic information, facilitating efficient and hassle-free travel experiences [443].

Energy efficiency is a crucial consideration within the automotive sector, and the utilization of AI and ML techniques plays a significant role in enhancing the performance of hybrid and electric vehicles [444]. These technologies effectively regulate power consumption and recharge patterns, ultimately optimizing efficiency and range. Another notable advantage is the increased level of safety provided by AI/ML

Table 6
Nano-blended fuels Performance and Emission Characteristics

Ref	*Nanoparticle Name*	Fuel	ENGINE TYPE	*Quantity*	*BSFC*	*BTE*	*EGT*	*CO*	*NOx*	*HC*	*CO_2*
[396]	Al_2O_3	30 % Jatropha biodiesel + 70 % diesel	4-stroke, single-cylinder diesel engine	50 ppm	Rise	Rise	–	Lowered	Lowered	Rise	–
[397,398]	methanol, ammonia, and hydrogen	Diesel (100 %)	4-stroke, single-cylinder diesel engine	*70 ppm*	Rise	Rise	–	Lowered	Lowered	Rise	–
[399]	CNT	WCO biodiesel (20 %) + Diesel (80 %)	4- stroke, Single cylinder, diesel engine	100 ppm	Rise	Rise	–	Lowered	Lowered	Rise	–
	Al_2O_3			100 ppm	Rise	Rise	–	Lowered	Lowered	Lowered	–
	CNT (50 %) + Al_2O_3 (50 %)			100 ppm	Rise	Rise	–	Lowered	Lowered	Lowered	–
[400]	CuO	Waste cooking oil biodiesel (20 %) + Diesel (80 %)	VCR, DI Diesel engine	20 ppm	Rise	Rise	Rise	Lowered	Lowered	Lowered	Rise
	CuO			30 ppm	Rise	Rise	Rise	Lowered	Lowered	Lowered	Rise
	CuO			40 ppm	Rise	Rise	Rise	Lowered	Lowered	Lowered	Rise
[401]	soot	Diesel (100 %)	HSDI diesel engine	*100 ppm*	Rise	Rise	–	–	Lowered	Rise	
[402]	CeO_2	Diesel (100 %)	4-Stroke, Singale Cylinder, Air cooling, DI Diesel Engine	15 ppm	Rise	Rise	Lowered	Lowered	Lowered	–	–
	CeO_2			25 ppm	Lowered	Rise	Lowered	Lowered	No change	–	–
	CeO_2	Orange Peel Biodiesel (100 %)		15 ppm	Rise	Rise	Lowered	Lowered	Lowered	–	–
	CeO_2			25 ppm	Rise	Rise	Lowered	Lowered	Rise	–	–
[403]	CeO_2	Hydrogen peroxide (1.5 %) + Waste cooking oil biodiesel (20 %) + Diesel (78.5 %)	Single Cylinder, 4-Stroke, Water cooling, DI Diesel Engine	40 ppm	Lowered	Rise	Rise	Lowered	Lowered	Lowered	Rise
	CeO_2			80 ppm	Lowered	Rise	Rise	Lowered	Lowered	Lowered	Rise
[404]	GO	Waste cooking oil biodiesel (15 %) + Diesel (85 %)	4-Stroke, Singale Cylinder,, diesel engine.	100 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	–
	GO			500 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	–
	GO			1000 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	–
[405]	CuO	Parsely biodiesel (20 %) + Diesel (80 %)	Single Cylinder, 4-Stroke, DI, Diesel Engine, Air Cooling	50 ppm	Lowered	Lowered	–	Lowered	Lowered	Lowered	Rise
	CuO			100 ppm	Lowered	Lowered	–	Lowered	Lowered	Lowered	Rise
[405]	TiO_2	Diesel (80 %) + Waste cooking oil biodiesel (20 %)	Single Cylinder, 4-Stroke, Diesel Engine, Air cooling	25 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	TiO_2			50 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	TiO_2			100 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	Al_2O_3			25 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	Al_2O_3			50 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	Al_2O_3			100 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	CNT			25 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	CNT			50 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	CNT			100 mg/L	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
[406]	CeO_2	Diesel (100 %)	4-Stroke CRDI diesel engine	40 ppm	Rise	–	–	Rise	Lowered	Lowered	–
	CNT			40 ppm	No change	–	–	Lowered	Lowered	Lowered	–
[407]	CuO	Diesel (80 %) + Tomato Biodiesel (20 %)	Single Cylinder water cooling 4-Stroke, diesel engine	40 ppm	Rise	Rise	–	Rise	Lowered	Rise	
	CuO			80 ppm	Rise	Rise	–	Rise	Rise	Lowered	
	CuO			120 ppm	Rise	Rise	–	Lowered	Rise	Lowered	
[408]	GNP	Diesel (40 %) + Butanol (20 %) + WCO biodiesel (40 %)	3-cylinder, Water-cooling, II diesel engine	100 ppm	Lowered	Rise	–	Rise	Lowered	–	Rise
	C			100 ppm	Lowered	Rise	–	No change	Lowered	–	Rise
[409]	*CNT*	MWCNTs-COOH nanoparticles + B5 biodiesel blend	CI single-cylinder engine	30 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				60 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				90 ppm	Rise	Rise	–	Lowered	Lowered	Rise	
[410]	Sr@ZnO	Diesel (80 %) + Castor biodiesel (20 %)	BS-IV, 4-Stroke, Single cylinder, water-cooling diesel engine.	30 ppm	Rise	Lowered	–	Rise	Rise	Rise	Rise
	Sr@ZnO			60 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	Lowered
	Sr@ZnO			90 ppm	No change	Lowered	–	Rise	Rise	Rise	Rise

(*continued on next page*)

Table 6 (*continued*)

Ref	*Nanoparticle Name*	Fuel	ENGINE TYPE	*Quantity*	*BSFC*	*BTE*	*EGT*	*CO*	*NOx*	*HC*	*CO_2*
[113]	GO	Sapota seed oil biodiesel (20 %) + Diesel (80 %)	Single cylinder, 4-Stroke, diesel engine	50 ppm	Rise	Lowered	–	Rise	Lowered	Lowered	Rise
[411]	TiO_2	Diesel (80 %) + Manilakarazpotat biodiesel (20 %)	Single cylinder, 4-Stroke, water-cooling diesel engine	50 ppm	Rise	Lowered	–	Rise	Lowered	Rise	Rise
	TiO_2			75 ppm	Rise	Lowered	–	Rise	Lowered	Rise	Rise
	TiO_2			100 ppm	Rise	Lowered	–	Rise	Lowered	Rise	Rise
[412]	AgSCN	Diesel (50 %) + WCO biodiesel (50 %)	DI diesel engine, Single cylinder, 4-Stroke, water-cooling.	200 ppm	No change	Rise	Lowered	Lowered	Lowered	Lowered	Lowered
	AgSCN			400 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	Lowered
	AgSCN			600 ppm	Rise	Rise	Lowered	Lowered	Lowered	Lowered	Lowered
[413]	GNP	Palm oil biodiesel (30 %) + Dimethyl carbonate (10 %) + Diesel (60 %)	4-Stroke, Single cylinder, water-cooling, DI Diesel Engine	40 ppm	Rise	Rise	–	Lowered	Lowered	Rise	–
	GNP			80 ppm	Rise	Rise	–	Lowered	Lowered	Rise	–
	GNP			120 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
[414]	TiO_2	Diesel (89.8) + Surfactent (0.2 %) + Water (10 %)	DI diesel engine, Single cylinder, 4-Stroke,	30 ppm	Rise	Rise	–	Lowered	Lowered	Rise	–
	TiO_2			60 ppm	Rise	Rise	–	Lowered	No change	Rise	–
	TiO_2			90 ppm	Rise	Rise	–	Lowered	Rise	No change	–
[415]	CuO	Diesel (100 %)	Naturally-aspirated DI diesel engine	1000 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	–
	CuO			2000 ppm	Lowered	Rise	Lowered	Lowered	Lowered	Lowered	–
[416]	FFO	Chicken fat biodiesel (20 %) + Diesel (80 %)	4-stroke Vertical, diesel engine.	50 ppm	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
	FFO			100 ppm	Rise	Lowered	Lowered	Lowered	Rise	Lowered	–
	FFO			150 ppm	Rise	Lowered	Rise	Lowered	Rise	Lowered	–
[417]	Al_2O_3	Butanol (20 %) Diesel (80 %) blend.	4-Cylinders, water-cooling, DI diesel engine,	30 mg/L	Lowered	Rise	–	Lowered	Lowered	Lowered	Rise
	Al_2O_3			50 mg/L	Lowered	Rise	–	Lowered	Lowered	Lowered	Rise
	Al_2O_3			100 mg/L	Lowered	Rise	–	Lowered	Lowered	Lowered	Rise
[418]	Al_2O_3	Jatropha biodiesel (20 %) + Ethanol (10 %) + Diesel (70 %)	Single cylinder DI diesel engine	10 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
	Al_2O_3			20 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
	Al_2O_3			30 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
[419]	Nanoalumina (Al_2O_3)	diesel engine fuelled by combined non-edible blends with nanoparticles	CI engine	25 ppm	Rise	Rise	Lowered	Lowered	Lowered	Rise	
[420]	Cerium oxide nanoparticle	blends of Grape Seed Oil Bio-diesel (GSO) with the additives Aluminum oxide	CI engine	20 PPM	Rise	Rise	Rise	Lowered	Lowered	Rise	
[421]	Al_2O_3	Diesel (100 %)	Diesel engine, single-cylinder, 4-stroke	30 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				60 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				90 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
[421]	Fe_2O_3	Diesel (100 %)	Diesel engine, single-cylinder, 4-stroke	30 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				60 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
				90 ppm	Rise	Rise	Rise	Lowered	Lowered	Rise	
[422]	Al_2O_3	Diesel (100 %)	DI diesel engine, four-cylinder, 4-Stroke, water-cooling.	50 ppm	Lowered	Rise	–	Lowered	Rise	Lowered	–
	Al_2O_3			100 ppm	Lowered	Rise	–	Lowered	Rise	Lowered	–
	ZnO			50 ppm	Lowered	Rise	–	Lowered	Rise	Lowered	–
	ZnO			100 ppm	Lowered	Rise	–	Lowered	Rise	Lowered	–
[423]	GO	Waste cooking oil biodiesel (20 %) + Diesel (80 %)	Twin-cylinder, 4-stroke turbocharged diesel engine	20 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
	GO			40 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
	GO			60 ppm	Rise	Lowered	–	Lowered	Rise	Lowered	–
	GNP			20 ppm	Rise	Lowered	–	Lowered	Lowered	Lowered	–
	GNP			40 ppm	Rise	Lowered	–	Lowered	Lowered	Lowered	–
	GNP			60 ppm	Rise	Lowered	–	Lowered	Lowered	Lowered	–
[424]	TiO_2	Tamanu biodiesel (30 %) + Diesel (70 %)	Two-cylinder, 4-stroke, DI diesel engine	25 ppm	–	–	–	Rise	Lowered	Rise	Lowered
	TiO_2			50 ppm	–	–	–	Lowered	Lowered	Lowered	Lowered
	TiO_2			75 ppm	–	–	–	Lowered	Lowered	Rise	Lowered
	TiO_2			100 ppm	–	–	–	Lowered	Lowered	Rise	Lowered
[425]	Al_2O_3	Polanga Biodiesel	Single cylinder Diesel engine	25 ppm	Lowered	Rise	–	Lowered	Lowered	Lowered	–
	Al_2O_3			50 ppm	Lowered	Rise	–	Lowered	Lowered	Lowered	–

(continued on next page)

Table 6 (*continued*)

Ref	*Nanoparticle Name*	Fuel	ENGINE TYPE	*Quantity*	*BSFC*	*BTE*	*EGT*	*CO*	*NOx*	*HC*	CO_2
[426]	CeO_2	Algae biodiesel (20 %) + Diesel (80 %)	DI Diesel Engine, 4-Stroke, Single Cylinder	25 ppm	Lowered	Rise	Rise	–	–	–	–
	CeO_2			50 ppm	Lowered	Rise	Rise	–	–	–	–
	CeO_2			75 ppm	Lowered	Rise	Rise	–	–	–	–
	CeO_2			100 ppm	Lowered	Rise	Rise	–	–	–	–
[427]	GNP	Dairy scum oil biodiesel (20 %) and Diesel (80 %)	Single cylinder, 4-Stroke, water-cooling diesel engine.	20 ppm	Rise	Lowered	–	Rise	Rise	Rise	–
	GNP			40 ppm	Rise	Lowered	–	Rise	Rise	Rise	–
	GNP			60 ppm	Rise	Lowered	–	Rise	Rise	Rise	–
[428]	TiO_2	Hydrogen (0.2 Kg) + Diesel (0.78 kg)	4-stroke, Single cylinder, CI Engine.	0.02 kg	Lowered	Rise	Rise	Lowered	Lowered	Lowered	Lowered
	CNT			0.02 kg	Lowered	Lowered	Rise	Lowered	Lowered	Lowered	Lowered
	Al_2O_3			0.02 kg	Lowered	Lowered	Rise	Lowered	Rise	Lowered	Lowered
	CuO			0.02 kg	Lowered	Lowered	Rise	Lowered	Rise	Lowered	Lowered
	CeO_2			0.02 kg	Lowered	Lowered	Rise	Lowered	Lowered	Lowered	Lowered
[429]	CNT	Jatropha biodiesel (20 %) + Diesel (80 %)	4-Stroke, Single cylinder, Air cooling, Diesel Engine	25 ppm	Rise	No change	Lowered	Lowered	Lowered	No change	–
	CNT			50 ppm	Rise	Rise	Lowered	Lowered	Lowered	Rise	–
	CNT			100 ppm	No change	Rise	Lowered	Lowered	Lowered	Rise	–
	TiO_2			25 ppm	Lowered	Rise	Lowered	Lowered	Rise	Lowered	–
	TiO_2			50 ppm	Rise	Rise	Lowered	Lowered	Lowered	Lowered	–
	TiO_2			100 ppm	Rise	Lowered	Lowered	Lowered	Rise	No change	–
	Al_2O_3			25 ppm	Lowered	Rise	Lowered	Lowered	Rise	Lowered	–
	Al_2O_3			50 ppm	Lowered	Rise	Lowered	Lowered	Lowered	No change	–
	Al_2O_3			100 ppm	Lowered	Rise	No change	Lowered	Rise	Rise	–

systems, which can detect signs of driver drowsiness, distraction, or impairment and take appropriate action when required [445]. Predictive analytics can proactively anticipate accidents by detecting and recognizing potential hazards, thereby providing recommendations for appropriate corrective measures. AI and ML models play a crucial role in enhancing engine performance to minimize fuel consumption and emissions, thereby making significant contributions to fuel efficiency and promoting environmental sustainability [446]. Furthermore, these technologies also contribute to the advancement of lightweight materials and the optimization of aerodynamic designs.

Supply chain optimization is a crucial application involving using AI to examine global supply chains [447]. The purpose of this analysis is to forecast and address potential disruptions, thereby facilitating an uninterrupted and efficient flow of parts and materials for the production of vehicles. AI in analysing customer data has proven advantageous in augmenting customer insights and refining marketing strategies [448]. This capability enables automakers to customize marketing campaigns and vehicle features to cater to distinct demographics and individual preferences. Within the realm of cyber security, artificial intelligence, and machine learning algorithms are employed to identify and avert cyber-attacks targeting interconnected vehicles and their corresponding systems, thereby safeguarding the security and reliability of vehicular data. As the automotive industry progresses, AI and ML will persist in playing a crucial role in augmenting safety, efficiency, and the overall user experience [449]. These emerging technologies have the potential to significantly advance innovation significantly, thereby exerting a profound influence on the future development of vehicle technology.

6. Role of AI/ML in Biodiesel-Nanofluid combustion

6.1. Different AI models used for biodiesel production and application

As discussed earlier, there are several studies that have applied AI and ML models to biodiesel production and application [450,451]. Artificial Neural Network (ANN) is a machine learning model inspired by the structure and function of the human brain. Comprising interconnected nodes or artificial neurons arranged in layers, ANN mimics the biological neurons, facilitating complex information processing. Multi-Layer Perceptron Neural Network (MLPNN) represents an architecture within artificial neural networks, characterized by multiple hidden layers. This design empowers MLPNN to learn intricate nonlinear relationships between input and output data, enhancing its capacity for complex pattern recognition. Another variant, Radial Basis Function Neural Network (RBFNN), utilizes radial basis functions in its hidden layer, enabling efficient function approximation, particularly beneficial for specific applications.

Adaptive Neuro-Fuzzy Inference System (ANFIS) represents a hybrid model seamlessly integrating the learning capabilities of neural networks with the rule-based structure of fuzzy logic systems. This integration empowers ANFIS to effectively model complex systems, offering a versatile approach to problem-solving. Extreme Learning Machine (ELM) is a feedforward neural network renowned for its rapid training speed, attributed to its single-hidden layer architecture with randomly chosen weights and analytically determined output weights. Kernel Extreme Learning Machine (KELM) extends the capabilities of ELM by incorporating the kernel trick from support vector machines, facilitating efficient handling of high-dimensional data.

Support Vector Machine (SVM) is a potent machine learning algorithm designed for classification and regression tasks. Recognized for its ability to find optimal hyperplanes separating data points of different classes, SVM is a versatile tool in various domains. Relevance Vector Machine (RVM) is closely related to SVMs but employs a distinct approach to model selection. By identifying a sparse subset of relevant training data points, RVM aims for better generalization and reduced computational complexity compared to standard SVMs. Least Squares Support Vector Machine (LSSVM) is a variant of SVM solving optimization problems using least squares principles, often leading to faster training times.

Bidirectional Recurrent Neural Network (BRNN) is a specialized type of recurrent neural network capable of processing information in both forward and backward directions. This bidirectional processing enhances BRNN's effectiveness in modeling sequential data, such as time series. Additive Multi-Task Learning (AMT) is a machine learning framework facilitating the simultaneous learning of multiple related tasks. This approach aims to improve overall performance by addressing tasks collectively, avoiding the limitations of learning tasks independently.

Lastly, Genetic Algorithm (GA) serves as a search heuristic inspired by natural selection processes. Widely used in computer science and artificial intelligence, GA iteratively evolves a population of potential solutions to find optimal solutions for complex problems. These techniques offer a diverse range of capabilities and are employed in various applications across different domains.

Table 7 presents an overview of various AI models employed for predicting the quality of biodiesel. Conversely, Table 8 delves into the inherent drawbacks and significance associated with utilizing AI/ML models for biodiesel quality predictions. This comparative analysis equips readers with a comprehensive understanding of the strengths and limitations of these models in this specific application domain. Multiple researchers have explored the application of MLPNN for estimating FAME conversion, a mechanical stirring process involving various oils and fats. This method utilizes suitable catalysts to convert fatty acids. Previously, RSM served as the prevalent technique for estimating ester conversion [452]. However, comparative studies between RSM and MLPNN for ester conversion in the mechanical mixing method have been conducted by several researchers. These investigations have established that while RSM remains a viable approach, MLPNN offers superior predictive capabilities for ester conversion in certain scenarios. The authors acknowledge the effectiveness of RSM but highlight the potential advantages of MLPNN in specific cases, suggesting its potential as a more refined estimation tool.

Fig. 23 depicts an artificial intelligence/machine learning (AI/ML) model designed to analyze the performance and pollutant parameters of a diesel engine fueled by biodiesel. The growing interest in biodiesel as a substitute fuel stems from its potential environmental and economic benefits [469]. This review further explores the application of ML techniques to optimize performance, efficiency, and emissions in biodiesel-powered diesel engines. Various approaches are being investigated to address challenges associated with biodiesel combustion and enhance engine operation [470]. The findings demonstrate the effectiveness of machine learning in:

- **Predicting engine performance parameters:** ML models can accurately forecast engine performance metrics relevant to biodiesel operation.
- **Optimizing combustion processes:** These models can identify strategies to optimize combustion processes for improved efficiency and reduced emissions in biodiesel engines.

Table 7
Biodiesel quality prediction by different AI models

AI/ML model	Catalysts	Feedstock	Outcome	Refs.
AMT model	Various catalysts	Various feedstock	FAME	[453]
BRNN model	KOH	Esterified ceiba pentandra oil	FAME	[454]
ELM	KOH	Palm-sesame oil	FAME	[455]
ELM model	NaOH	WCO	FAME/ FFAEE	[456]
GA-tuned LSSVM model	H_2SO_4	Castor oil	FAME	[457]
KELM model	KOH	Esterified ceiba pentandra oil	FAME	[458]
MLPNN and RSM model	KOH	Degummed sterculia foetida oil	FAME	[453]
MLPNN and RSM model	NaOH and KOH	Palm kernel oil	FAME	[454]
Model Takagi-Sugeno ANFIS	KOH	Jatropha-Algae oils mixture	FAME	[459]
Model Takagi-Sugeno ANFIS	KOH	Palm oil	FAME	Ref
RBF Kernel SVM model	NaOH	WCO	FAME	[453]
Single-hidden MLPNN model	H_2SO_4	African pear seed oil	FFA	[454]

Table 8
Drawbacks and Significance of AI / ML-based models for predictions of biodiesel.

Model type	Drawbacks	Significance	Refs.
ANFIS	Sensitive to ambiguous rules and input factors, large datasets needed Complex computation with significant input variables.	Model complicated and fuzzy systems, Handle huge noisy data sets.	[460]
AMT	Univariate nodes for decision-making restrict use.	Powerful boosted and decision-tree algorithm, simple to comprehend	[461]
BRNN	More complex than classical ANN models, Insensitive,	Highly exact, no validation step or network weights, autonomous model selection, model structure insensitive, resilient	[462]
ELM	Overfitting, unclear hidden layer structure, outlier sensitivity, massive data limitations, random weights and input bias, unsteady prediction.	Don't need tuning Rapid weight adjustment, easy implementation,	[463]
KELM	Slow, difficult on vast data, predictions relies on kernel functions and noise-sensitive parameters.	More accurate generalization than ELM, Few parameters, relaxed restrictions, fast feature extraction, no hidden node estimate.	[464]
LSSVM	Strongly depending on kernel function and regularization settings, Outlier sensitivity, unsuitable for large datasets	Model simplicity, Manage small samples, more accuracy than SVM, faster training.	[465]
MLPNN	Poor extrapolation, huge dataset, trial-and-error for discover layers and neurons, longer iteration, require normalization.	Simple structure, efficient interpolation, minimal parameters, implementable.	[466]
RBFNN	Data noise sensitive, difficult as hidden units rise, requiring hyper parameters and centers	Simple, flexible model with few parameters, no iterations, and no weights for optimization.	[467]
SVM	Non-systematic, initialization-sensitive kernel function selection Slow for large datasets, unable when number of attributes exceeds data samples.	Classification-friendly, mathematically traceable, precise problems	[468]

- **Reducing emissions:** ML approaches can contribute to emission reduction efforts by identifying and mitigating factors that contribute to pollutant formation during biodiesel combustion.

Furthermore, the study offers valuable insights into the strengths and limitations of each machine learning technique when applied to biodiesel-powered engines [471]. The results highlight the potential of machine learning as a valuable tool for promoting the broader adoption of biodiesel in internal combustion engines, ultimately paving the way for cleaner and more sustainable transportation systems.

6.2. AI/ML models for estimation of fuel properties

Fig. 24 illustrates the sequential procedure for biofuel parameter forecasting using ML techniques. The initial step involves inputting experimental biofuel data. This data then undergoes a refinement process, where noise, extraneous information, and missing values are removed. Subsequently, the second phase involves developing a suitable ML algorithm based on the refined biofuel parameters. This phase assesses multiple candidate algorithms to determine the most effective one, potentially involving the use of multiple ML algorithms.

Utilizing current experimental methods to assess a physic-chemical

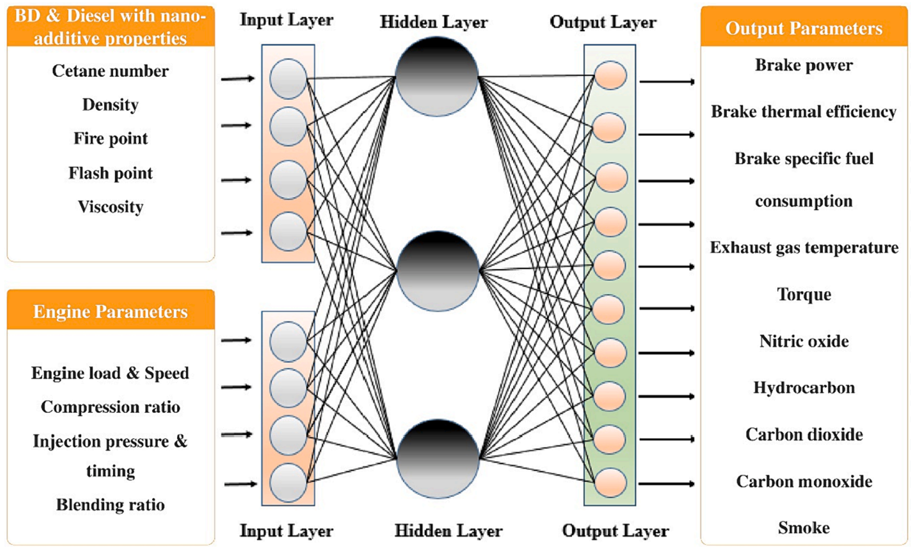

Fig. 23. Various AI/ML model for diesel engine emission and performance characteristics.

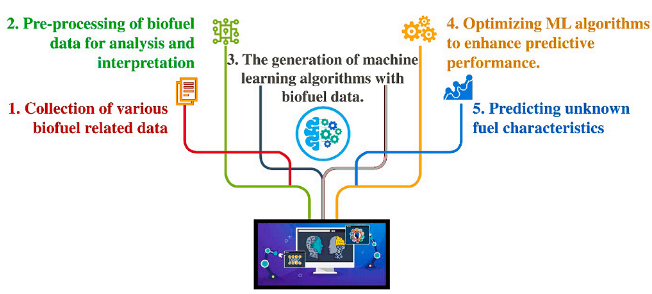

Fig. 24. Various steps in ML-based prediction of biofuel properties.

properties of biodiesel and its contaminants are both time-intensive and expensive. The study by Bukkarapu and Krishnasamy [167] emphasized the significance of predicting the fuel properties of biodiesel. This work highlighted the necessity of utilizing a schematic representation, as depicted in Fig. 25, to facilitate this prediction process. The study emphasized the need for precise predictions in informing judgments on the adherence to ASTM standard limits for feedstock process parameters.

The biodiesel quality heavily relies on a composition of fatty acids of original oil. This implies that the efficiency of combustion and the qualities of the fuel are closely interconnected with the composition of fatty acids. For biodiesel to attain commercial viability, it must adhere to established criteria, including but not limited to ASTM D6751 and EN 14214 requirements. Achieving compliance with these requirements necessitates the accurate quantification of diverse attributes. Nevertheless, biodiesel's complex and diverse structure, which frequently includes impurities such as unreacted catalysts, glycerin, various glycerides and alcohols [472], poses a challenge in developing a universally applicable model for predicting these features. However, the digital age has provided opportunities to address this difficulty. The utilization of sophisticated computational approaches and algorithms, particularly within the field of machine learning, has become increasingly significant in the estimation of biodiesel characteristics. However, at present, these applications have predominantly focused on predicting attributes such as density, viscosity, cetane number, and oxidation stability, among several others.

Several studies have explored the application of computational approaches in predicting the properties of biodiesel. For example, researchers have investigated quantitative techniques to determine the cetane number of different biodiesel varieties [473]. Ramadhas et al. [474] conducted a study exploring the utilization of ANN models, specifically focusing on their intricate network designs, such as multilayer

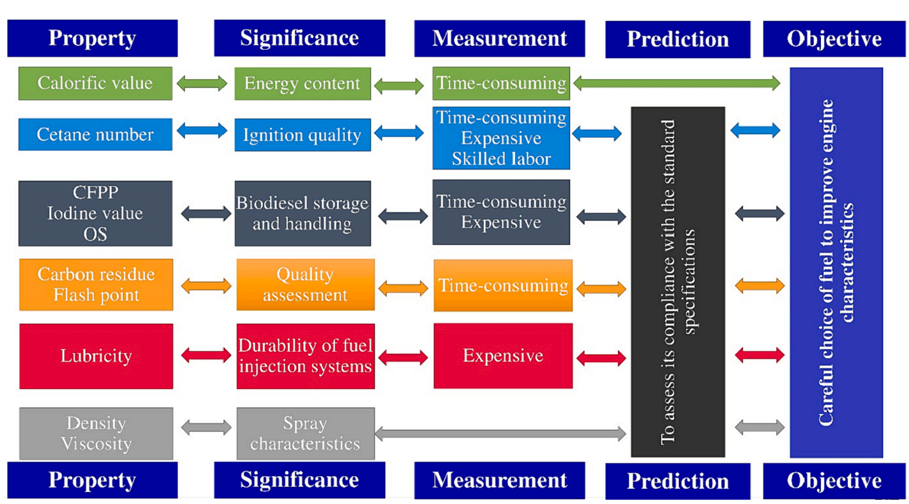

Fig. 25. Importance of AI/ML model for biodiesel fuel properties prediction [167]

feedforward and radial base, to predict cetane quantities. The results of their study demonstrated a significant level of precision in forecasting, thereby reinforcing the potential of ANN models. Freedman and Bagby [475] proposed a theoretical framework for predicting the saturated methyl esters cetane number on the basis of carbon atoms number in the molecules. Cetane numbers for saturated methyl esters can be expected by considering specific features. However, existing techniques exhibit a notable underestimation in determining the cetane numbers for biodiesels that contain a high proportion of unsaturated methyl esters. In a previous investigation, Klopfenstein [476] correlated a saturated methyl esters' chain length and their cetane number. It was observed that there exists a non-linear relationship between the cetane number and the carbon atoms number.

In a related context, Bobadilla et al. [38] integrated SVM with linear regression techniques. The study primarily centered around the prediction of biodiesel yield and key attributes like viscosity and heating value. The researchers discovered that the incorporation of algorithms into regression models resulted in more accurate predictions. A dynamic viscosity of primary unsaturated and saturated biodiesel methyl ester components at 313 K was determined by studies done by Allen et al. [477]. Their study revealed a significant relationship between the dynamic viscosity, the double bonds number in unsaturated esters and the molecular weight of saturated esters. A maximum inaccuracy of 17 % was reported while assessing dynamic viscosity of 19 distinct biodiesels. Cheng et al. [478] conducted a significant study in which they employed K-means Chaotic Genetic Algorithm (KCGA) and Evolutionary Support Vector Machine Inference Model (ESIM) to create the GA-ESIM methodology. The findings demonstrated that the GA-ESIM model surpassed alternative artificial intelligence-based methodologies regarding predictive precision.

Numerous studies have demonstrated the accuracy of machine learning algorithms in predicting diverse biodiesel qualities. Wand and Alruyemi [479] conducted an investigation on the application of Gaussian process regression (GPR) techniques for the estimation of biodiesel density. Their findings revealed that the GPR model exhibited greater predictive accuracy compared to alternative methods. Giwa et al. [480] employed ANN to forecast attributes such as cetane quantity and flash point, attaining accuracies over 95 %. Several researchers have proposed various indicators to determine the composition of biodiesel, such as the polyunsaturated esters (PU), number of double bonds (N), monounsaturated esters (MU) and the carbon atom count (C). These indicators aim to establish a relationship with the biodiesel's flashpoint temperature [481,482,483]. Demirbas [484] offered two independent models that correlated biodiesel flashpoint temperature, density, and viscosity. The models had R^2 values of 0.9357 and 0.8753. In contrast, Pinzi et al. [481] validated their model using data from six biodiesels sourced from existing literature. The validation process was limited to a slight temperature range of 443–458 K. Aulia et al. [485] attempted to estimate the biodiesel flashpoint temperature using an approach similar to that employed in previous research. However, the findings revealed an increased prediction error of 15 %. In addition, some scholars have explored the possibility of estimating the biodiesel flashpoint temperature by using other easily measurable characteristics. Chakraborty and Banerjee [486] conducted an experiment producing 25 soybean oil samples under different conditions. Subsequently, they examined the relationship between the flashpoint temperatures of these samples and their viscosity and density, which were determined at a temperature of 300 K.

The investigation of oxidation stability, a crucial characteristic of storage considerations, has also been a primary focus of scholarly inquiry. In their study, Camur and Al-Ain [487] conducted an empirical investigation utilizing several machine-learning models to forecast biodiesel's oxidative stability and its mixes. Based on the examination of 39 samples, it was determined that the RBFNN model had the highest level of accuracy in forecasting oxidative stability. In their study, Sarin et al. [488] predicted the biodiesel induction duration. These models incorporate two key factors: the total unsaturation and the percentage mass of methyl palmitate. A linear model established a correlation between the biodiesel induction period and methyl palmitate mass percentage. This model was relevant for biodiesel compositions, including methyl palmitate up to a maximum of 45 %. The model demonstrated a coefficient of determination R^2 of 0.994 when evaluated using training dataset. Likewise, model based on their TU (Thermogravimetric Unit) was appropriate for biodiesel, with a maximum TU of 84 %. This resulted in an R^2 value of 0.998 for the training set indicating a strong correlation [488]. Gulsen et al. [489] proposed developing an augmented linear model for estimating the biodiesel induction period. The model utilized input variables, including the mass percentage of methyl linoleate, and natural antioxidants like tocotrienol-TT and tocopherol-γT.

Therefore, the increasing significance of ML techniques in predicting biodiesel properties, such as density, viscosity, cetane number, and oxidation stability. ML algorithms have been employed to develop accurate predictive models, enabling informed decision-making in biodiesel production and quality control. The integration of computational approaches and sophisticated algorithms addresses the challenges posed by biodiesel's complex composition, paving the way for more efficient and sustainable fuel production processes. Through various studies, ML models have demonstrated remarkable precision in forecasting biodiesel qualities, underscoring their potential in advancing the field of renewable energy.

7. Challenges and future perspectives

7.1. Current challenges in biodiesel-nanofluid combustion research

Biodiesel-nanofluid combinations must be stable since nanoparticle sediment impacts fuel quality and combustion. Nanoparticle sedimentation averages 0.5 % per hour, affecting combustion quality. Even though biodiesel is a cleaner option, adding nanoparticles may result in an uneven combustion efficiency. Biodiesel engine combustion parameters are not commonly explored with ML due to equipment integration issues in the combustion chamber. ML studies on PM and smoke emissions vary in focus, including PM fractions [490], PM level [491,492] and smoke measurements [493–496], making comparisons difficult. Biodiesel engine emissions, unregulated in literature, cause serious health effects. Depending on the biodiesel and nanoparticles, biodiesel-nanofluid combustion is 5–15 % less efficient than diesel fuel. Biodiesel-nanofluids reduce particulate matter but increase nitrogen oxides, aggravating issues. While biodiesel-nanofluids can lower CO and PM emissions by 30 %, NOx emissions can rise 5–10 %. These fluids also affect engine wear and material compatibility, potentially speeding up component degradation. When employing biodiesel-nanofluids instead of diesel, cylinder and piston wear rates are 2–5 % higher. Because nanoparticles cost more, biodiesel-nanofluids are less economically viable for large-scale use. Some research found that biodiesel-nanofluid mixes increased IC engine fuel consumption by 7 %. Scalability challenges include nanoparticle dispersion and fuel stability. The combination of biodiesel with nanofluids is not regulated. Hence, the need for standards may hinder the adoption of nanotechnology in fuels.

7.2. Potential areas for future research and development

Currently, there is ongoing research on using nanoparticles to enhance biodiesel-nanofluid combinations. Research could create nanoparticles with better thermal and optical qualities. Biodiesel-nanofluid engines' combustion processes are yet unclear. Future studies could use time-resolved measurements to understand combustion processes better, leading to more efficient and cleaner engines. Existing biodiesel-nanofluid combustion technologies are 70–80 % efficient. Through AI/ML models, targeted studies could enhance this by at least 10 %. Real-world applications of these technologies are a huge step beyond lab settings. Piloting and testing fuel technologies with automotive manufacturers are essential to demonstrate their feasibility and scalability. Emission control remains crucial. Use AI/ML algorithms in biodiesel-nanofluid IC engines to cut CO_2, NOx, and particulate matter emissions by 30 % in 5 years. Another important factor is thermal efficiency. Existing biodiesel-nanofluid mixes have potential but can be optimized to better compete with fossil fuels. Improve biodiesel-nanofluid heat transfer by 15 % to boost engine efficiency. Understanding the economic feasibility of mass-producing biodiesel-nanofluid combinations is crucial. Develop ways to reduce biodiesel-nanofluid production costs by 25 % over three years to make it more competitive with conventional fuels. Many studies have employed energy-based metrics, including BSFC, BP, and BTE, to evaluate performance. Due to their energy quantity focus, these measures may miss biodiesel engine performance details [497]. Exergetic efforts are becoming more popular [498,499], however, they ignore economic and environmental factors. Exergoenvironmental and Exergoeconomic strategies can integrate exergy concepts with economic and ecological concerns [500,501], recommending future studies. Numerous research [111,502–512] have raised concerns about non-quantitative inputs such as fuel type. This limitation prevents the model from adapting to changes in fuel composition. Salam and Verma [513] used Diesel-RK data, which violates data-driven ML principles. Valid experimental data should underpin ML models. Finally, hybrid ML models, which improve traditional models, are growing. Future studies should significantly focus on using ML for real-time biodiesel engine management and monitoring to determine efficient blending ratios. For widespread adoption to occur, it is necessary to conduct comprehensive cost-benefit analyses and long-term sustainability studies. Another critical study area is regulatory guidelines. As new fuel technologies become commercialized, comprehending their legal and regulatory implications requires a multidisciplinary approach involving law, policy, and engineering.

8. Integration pathways of AI/ML in nanoparticle infused biodiesel production and utilisation

The integration of AI/ML in nanoparticle-infused biodiesel offers exciting possibilities for optimizing production processes, enhancing fuel properties, and improving engine performance. Here, we explore the fundamental pathways that underpin this integration:

1. Nanoparticle design and Selection:
- AI/ML algorithms can analyze vast datasets comprising nanoparticle properties, feedstock characteristics, and desired fuel performance objectives. This enables:
  - o **Predicting optimal nanoparticle characteristics:** Machine learning models can identify the size, shape, composition, and surface functionalization of nanoparticles that optimize key fuel properties like stability, viscosity, and combustion efficiency.
  - o **Recommending suitable nanoparticle materials:** AI models can analyze various nanoparticle materials and predict their compatibility with specific feedstocks and production processes, ensuring efficient integration.
2. Production process optimization and Control:
- AI/ML can monitor and optimize various stages of nanoparticle-infused biodiesel production in real-time, ensuring efficient nanoparticle incorporation and consistent fuel quality. This involves:
  - o **Predictive maintenance:** Machine learning algorithms can analyze sensor data to predict equipment failures and enable proactive maintenance, preventing disruptions and ensuring smooth nanoparticle integration.
  - o **Optimizing reaction parameters:** AI models can analyze process parameters like temperature, pressure, mixing protocols, and nanoparticle dosage to identify optimal conditions for maximizing nanoparticle dispersion and stability within the biodiesel.
3. Quality control and Prediction:
- AI/ML can be employed to ensure consistent quality of nanoparticle-infused biodiesel throughout the production process. This involves:
  - o **Real-time quality monitoring:** Machine learning models can analyze sensor data to monitor key quality parameters like nanoparticle distribution, fuel stability, and potential agglomeration issues.
  - o **Predicting fuel properties:** AI models can be trained on data linking nanoparticle characteristics, production conditions, and desired fuel properties. This enables prediction of key parameters like cetane number, lubricity, and cold flow properties, facilitating proactive adjustments to maintain consistent quality.
4. Engine performance optimization and emission Reduction:
- AI/ML can play a crucial role in optimizing engine performance and reducing emissions when using nanoparticle-infused biodiesel. This includes:
  - o **Predicting engine behavior:** Machine learning models can predict engine parameters like power output, fuel efficiency, and emission profiles based on engine operating conditions, fuel properties, and nanoparticle characteristics.
  - o **Developing adaptive engine control strategies:** AI models can be used to develop engine control strategies that adjust parameters like injection timing, combustion temperature, and air–fuel ratio in real-time to optimize performance and minimize emissions for nanoparticle-infused biodiesel blends.
5. Life cycle assessment and Sustainability:
- AI/ML can be harnessed to assess the environmental impact of nanoparticle-infused biodiesel production and utilization across its entire life cycle. This involves:
  - o **Modeling life cycle parameters:** Machine learning models can be used to estimate factors like energy consumption, potential environmental risks associated with nanoparticle production, and overall greenhouse gas emissions of the nanoparticle-infused biodiesel pathway.
  - o **Identifying sustainable practices:** AI models can analyze data to identify and recommend sustainable practices throughout the nanoparticle-infused biodiesel lifecycle, minimizing environmental impact and ensuring responsible production processes.

By leveraging AI/ML capabilities for data analysis, prediction, and optimization, the integration of these technologies holds immense potential for the development of next-generation nanoparticle-infused biofuels. This paves the way for a more efficient, sustainable, and environmentally conscious biofuel industry, contributing to cleaner transportation and a greener future.

9. Conclusion

Biodiesel, derived from organic sources through transesterification, is a low-emission and environmentally sustainable fuel, presenting a compelling alternative to traditional diesel. Its positive environmental impact is evident in its biodegradability, non-toxic nature, and demonstrable reduction of greenhouse gas emissions and harmful pollutants compared to petroleum-based diesel. With lower sulfur, particulate matter, and aromatic content, biodiesel contributes to improved air quality and reduced health risks. The inherent renewability of biodiesel, sourced from renewable feedstocks like soybean, canola, palm, and used cooking oil, offers a continuous production cycle, minimizing dependence on finite fossil fuels and enhancing energy security. Biodiesel's compatibility with existing engines and infrastructure, serving as a drop-in replacement or blend with petroleum diesel, enables its seamless utilization across various sectors. Promising feedstocks like algae or waste oils further contribute to a stable carbon cycle, with the potential for carbon neutrality or negativity. The remarkable compatibility of biodiesel with diesel vehicles, requiring only minor adjustments, ensures optimal performance, engine longevity, and efficiency.

Nanofluids, consisting of nanoparticles dispersed in a base fluid, offer transformative possibilities for internal combustion engines. Metal oxide nanoparticles are stable and have high thermal conductivity, making them effective for improving heat transfer. They can also reduce emissions by acting as catalysts for the combustion process. Noble metal nanoparticles, such as gold, silver, and copper, have excellent thermal conductivity and catalytic properties. They can improve combustion efficiency and reduce emissions. CNTs have exceptional thermal conductivity and mechanical strength, making them ideal for nanofluids used for engine cooling and lubrication. They can also improve combustion and reduce emissions. GNPs have high thermal conductivity and mechanical strength, similar to CNTs. They can improve engine cooling, reduce friction and wear, and potentially lead to smaller and lighter engines. Hybrid nanoparticles combine the properties of different materials, such as a metal oxide core and a metal shell. They can offer synergistic benefits, such as improved heat transfer and catalytic activity. Challenges include achieving stable dispersion, but ongoing research aims to overcome obstacles and advance engine technology. Nanofluids incorporating these nanoparticles not only offer environmental benefits but also hold the potential to significantly enhance engine efficiency, making transportation more sustainable in the future.

The integration of Artificial Intelligence (AI) and Machine Learning (ML) has significantly impacted the automotive industry, revolutionizing vehicle development, manufacturing, safety, and driving experiences. In autonomous driving, AI and ML algorithms are pivotal, utilizing data from LiDAR, radar, cameras, and GPS for navigation, object recognition, and real-time decision-making. Advanced Driver Assistance Systems (ADAS) rely on these technologies for features like adaptive cruise control and lane-keeping assist. Predictive maintenance, enabled by AI, anticipates component failures, reducing downtime. In manufacturing, AI-powered robotics optimize production processes and quality control, while ML models enhance supply chain logistics. AI-driven infotainment systems provide tailored content and voice identification. In traffic management, AI analyzes real-time data for dynamic routing, reducing congestion. Energy efficiency in hybrid and electric vehicles benefits from AI/ML regulation of power consumption. These technologies also contribute to enhanced engine performance, minimizing fuel consumption and emissions. Supply chain optimization, customer insights, and cybersecurity are additional applications, emphasizing AI/ML's continued role in advancing safety, efficiency, and user experience in the automotive sector.

Biodiesel-nanofluid combinations face critical challenges, requiring stability to counter nanoparticle sedimentation that impacts fuel quality and combustion, resulting in 5–15 % lower efficiency than diesel. These combinations, while reducing particulate matter, increase nitrogen oxides, affecting emissions and engine wear. Cylinder and piston wear rates rise by 2–5 %, making biodiesel-nanofluids economically less viable. Additionally, they may increase IC engine fuel consumption by 7 %. Future research aims to enhance these combinations, create better nanoparticles, and understand combustion processes through AI/ML models. Real-world applications, emission control, and cost-benefit analyses are crucial for widespread adoption. AI/ML integration in real-time engine control systems focuses on adjusting parameters dynamically for optimal performance, preventive maintenance, and real-time emissions monitoring. Legislative support, seamless integration, and public awareness are key drivers, while research and development play a vital role in advancing technology and ensuring sustainability.

CRediT authorship contribution statement

Manzoore Elahi M. Soudagar: Writing – original draft, Writing – review & editing, Resources, Formal analysis, Conceptualization. **Sagar Shelare:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Deepali Marghade:** Writing – original draft, Investigation, Formal analysis, Data curation. **Pramod Belkhode:** Writing – original draft, Methodology, Investigation, Formal analysis. **Mohammad Nur-E-Alam:** Writing – original draft, Visualization, Validation. **Tiong S. Kiong:** Visualization. **S. Ramesh:** Supervision, Software, Resources. **Armin Rajabi:** Writing – review & editing, Validation. **Harish Venu:** Investigation, Formal analysis, Data curation, Conceptualization. **T.M. Yunus Khan:** Formal analysis, Data curation, Funding acquisition, Conceptualization. **MA Mujtaba:** Writing – review & editing, Validation. **Kiran Shahapurkar:** Software. **MA Kalam:** Project administration, Validation. **I.M.R. Fattah:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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