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A Comprehensive Study for the Algae-Ethanol Biofuels for Diesel Engines: Performance and Environmental Considerations.

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Abstract:
This comprehensive review investigates into the escalating field of algae-ethanol fuel blends for compression ignition (CI) engines, offering a detailed analysis of the studies conducted in this field. The addition of ethanol to algae based blends enhances their performance, combustion characteristics, and emissions. The collective findings emphasize the significant impact of algae-ethanol fuels on engine performance and emissions reduction. Blending algae-based biofuels with ethanol and diesel has consistently demonstrated favourable outcomes across various engine types. The B20 blend, comprising 20% ethanol and 80% diesel, has consistently exhibited enhanced brake thermal efficiency (BTE) and reduced emissions of nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). The optimization techniques studied, including response surface methodology (RSM), Taguchi method, and artificial neural networks (ANN), have proven effective in fine-tuning engine parameters to maximize efficiency and minimize emissions. Additives such as glycerol ethoxylate (GE), butylated hydroxytoluene (BHT), and n-pentanol have also been explored to enhance ignition and combustion characteristics. Life cycle analysis (LCA) studies have highlighted the environmental benefits of algae-ethanol fuels, showcasing reduced environmental impact compared to petroleum-based fuels. Biodiesel derived from algae exhibits the potential to enhance BTE by up to 5%, accompanied by significant reductions in CO, HC, and NOx emissions. Ethanol, when added to the mix, can further improve BTE by as much as 3%, with notable reductions in CO and HC emissions. The incorporation of nanoparticles such as CeO2 and Al2O3 has shown promise in enhancing engine performance and reducing emissions when added to algae-ethanol blends.
Keywords: Algae biofuel, ethanol, optimisation, nano particles, CI engine.

1. Introduction

The pursuit of ecologically sustainable and environmentally responsible energy resources has engendered heightened enthusiasm for biofuels originating from renewable resources. Within this spectrum, microalgae have commanded substantial interest due to their elevated lipid concentrations, expeditious growth kinetics, and capacity to alleviate carbon emissions via the sequestration of carbon dioxide (CO_2)[1]–[4].

This comprehensive study covers advancements and investigations within the domain of biofuels derived from microalgae, embracing examinations of their combustion behaviour, ecological implications, and prospective trajectories. The utilization of microalgae as a source of biofuels has been the subject of extensive investigation over the past few years. Researchers have explored various aspects of algae-based biofuels, ranging from the assessment of their combustion characteristics in internal combustion engines to the evaluation of their potential in reducing greenhouse gas emissions. This review integrates findings from a range of studies to provide a holistic perspective on the current state of knowledge in the field of algae biofuel and ethanol. In line with that NITI Aayog and the Ministry of Petroleum & Natural Gas has published report in June 2021 showcasing the roadmap for achieving 25% ethanol blending by 2025 and emphasis on the development of flex-fuel technologies [5].

The combustion performance of algae-based biofuels in different engine types has been a key focus of research efforts. Several studies have examined the use of algae oil and algae biodiesel as fuel alternatives internal combustion engines and concluded that algae oil and algae biodiesel have slightly higher brake thermal efficiency and low NOx emission comparatively.[1], [6], [7] .

Saraswat and Chauhan (2020) determined that the energy density of algae biofuel is approximately 5–8% lower when compared to that of petrol and diesel. The study's findings indicated that, across all blending ratios, the brake-specific fuel consumption (BSFC) of butanol and algae oil blends is higher than that of pure petrol under all operating conditions. This is primarily attributed to the lower calorific value of butanol and algae oil compared to petrol. The data also revealed similar properties between 5%, 10%, and 15% butanol-algae blends and pure gasoline. They found that algae biodiesel exhibits promising combustion stability and emission performance in a CI engine, with a significant reduction in particulate matter emissions [6]. Furthermore, the impact of blending algae-based biofuels with other conventional fuels, such as ethanol and diesel, has been explored extensively. Studies have investigated the effects of fuel blends on engine performance and emissions. They determined the BTE increased using blends upto 5% and BSFC is decreased uto 10% [8]–[10]. Rao et al. (2021) demonstrated that the addition of ethanol to Niger-Diesel blends at varying injection pressures resulted in improved engine performance and reduced emissions of nitrogen oxides. Their results indicated that upto 200 bar injection pressure, engine produces high brake power and beyond it performance deteriorates [9]. High ethanol levels resulted in intensified combustion noise and reduced combustion stability, as evident from cyclic variations. Especially, when the ethanol content reached 30%, there was a substantial increase in the coefficient of variation of peak pressure (COVpmax). While increasing ethanol content, soot emissions exhibited a noteworthy reduction ranging from 11.28% to 47.23%. However, this decrease was accompanied by an increase in NOx emissions ranging from 2.68% to 7.04%, as well as HC emissions rising by 9.99% to 21.47%. The study recommended that the ethanol blending ratio should not surpass 30% [11] This evaluation also covers the effect of additives/nanoparticles on the performance of the CI engine. Firew et al. (2022) revealed that the introduction of $NiZnFe_2O_4$ nanoparticles into ethanol-diesel emulsion decreased BSFC by 27.86% while simultaneously enhancing brake power by 7.74% and brake torque by 3.53%. [12].

On other hand Szwaja et al. (2022) scrutinized the effects of ethanol-glycerol blend combustion on the performance and exhaust emissions of a spark-ignited engine and revealed that the ethanol-glycerol blend at a ratio of 3:1 (75/25%) exhibits as promising alternate fuel for SI engine.[13]

In addition to performance considerations, this review addresses the environmental implications of algae-based biofuels. Algae cultivation presents an opportunity to utilize high-purity carbon dioxide sources, contributing to carbon capture and reducing net greenhouse gas emissions.in the comprehensive review on Current Strategies and Prospects in Algae for Remediation and Biofuels by Kandasamy et al. (2021) has discussed the advantages of algae cultivation like waste water treatment, Co2 absorption etc. They revealed the demerits like fuel production costing can be reduced by developing more efficient technology.[14] Ou et al. (2021) outlined the opportunities and challenges of utilizing high-purity CO_2 for algae cultivation and biofuel production in the United States [15]. Microalgae have the capacity to generate a range of biofuels, such as biodiesel, bioethanol, and bio-methane. Additionally, microalgae can serve as a means to capture carbon dioxide (CO_2) from the atmosphere. The cultivation of microalgae holds promise in satisfying approximately 20% of the world's demands for transportation fuels. Moreover, it has the potential to sequester as much as 10% of worldwide CO_2 emissions [16].

Furthermore, the use of low-lipid waste algae for energy production offers a sustainable approach to waste management. Kowthaman and Selvan (2020) conducted a kinetic study on the use of low-lipid waste algae for energy development, highlighting its potential as a green fuel source. Low-lipid waste algae can serve as a raw material for producing biofuels using pyrolysis. The activation energy required for the pyrolysis of low-lipid waste algae is notably low, falling within the range of 8.7 to 20.9 kJ/mol, indicating that the process can be initiated with ease. Pyrolyzing low-lipid waste algae can be accomplished at relatively modest temperatures, typically within the range of 300 to 500 °C, rendering it a more energy-efficient approach compared to other methods of biofuel production. [3].

Evaluations of life cycle assessments and cost analyses have been conducted to assess the environmental and economic viability of algae-based biofuels. The algal biofuels examined in the research displayed varying minimum fuel selling prices, spanning from $3.39 to $5.93 per gasoline gallon equivalent (GGE), liable on the chosen conversion route. In terms of greenhouse gas (GHG) emissions, the algal biofuels exhibited a considerable advantage over conventional gasoline, with emissions ranging from -0.0185 to 0.0383 kg CO_2-eq per MJ of fuel. [2], [17].

Bui et al. (2022) conducted a life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties, providing insights into the economic aspects of adopting alternative fuels. They concluded that dual fuel engine may be more cost effective [17]. This paper explores the future prospects and challenges associated with the widespread adoption of algae-based biofuels. It provides insights into strategies for optimizing microalgae cultivation and lipid production, as well as the development of advanced conversion technologies. Additionally, it discusses the role of algae-based biofuels in addressing climate change and enhancing energy security. By examining the combustion performance, environmental impact, and future prospects of these biofuels, this review aims to provide a comprehensive resource for researchers, policymakers, and stakeholders interested in the field of renewable energy.

2. Methodology

This study was motivated by an examination of the latest advancements and prospective obstacles concerning the utilization of algae-ethanol blended biofuels for compression ignition (CI) engines. To comprehensively comprehend the present advancements and imminent challenges, an in-depth analysis of contemporary literature was conducted as the primary information source. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), an established and recognized protocol for executing systematic literature reviews, was employed in this investigation.

This methodology employs meticulously structured approaches deliberately selected to mitigate biases, thereby ensuring the acquisition of precise information, culminating in the formulation of dependable and credible conclusions [18].

2.1: Approach to Conducting Literature Search

The current investigation was conducted by employing the Science Direct database, alongside supplementary sources. Notably, these databases are esteemed for their credibility and comprehensiveness, encompassing over 1520 publications within the energy domain and over 450 publications related to renewable energy sources, incorporating considerations of environmental sustainability. A search string was devised, leveraging our expertise in the pertinent field, and the specific formulation of this search string is detailed in the provided table 1.1.

Table 1.1: search methodology and results

Search steps	Search string	Boolean operator	Search Result
Initial Search	Algae fuel, Ethanol blend	AND, OR	42249
Year of publication considered (>2014)	Algae fuel, Ethanol blend	AND, OR	20192
Only journal publication	Algae fuel, Ethanol blend	AND, OR	2054
Impact factor (> 1.5)	Algae fuel, Ethanol blend	AND, OR	679
Accessibility (open access)	Algae fuel, Ethanol blend	AND, OR	62

Research review process involves a systematic refinement to gather relevant articles on algae-derived biofuels blended with ethanol for compression ignition engines. The initial phase encompassed a broad exploration using the search string "Algae fuel, Ethanol blend." Employing Boolean operators "AND" and "OR," we retrieved an extensive result of 42,249 records. Subsequently, search was narrowed by focusing to the desired timeframe (2014-2023), maintaining the same search string and Boolean operators.

Timeframe considered was chosen to study about the research conducted about the algae fuel and ethanol blend comprehensively. This step yielded 20,192 results. To enhance scholarly credibility, we limited the search to journal publications, persisting with the search string "Algae fuel, Ethanol blend," and the same Boolean operators. This process reduced the outcomes to 2,054 articles. Further refining our selection, we considered articles with an impact factor greater than 2, maintaining the consistent search string and Boolean operators. This filtration led to a subset of 679 relevant articles.

Ensuring our restrictions of accessibility, we concentrated solely on open access publications using the same search string and Boolean operators, ultimately identifying 62 suitable articles. A database with the articles containing titles, abstracts and full texts was created in Mendeley reference management software. This meticulous and progressively focused approach resulted in a refined collection, ensuring scholarly value, recent relevance, and availability for research work on algae-ethanol blended biofuels for compression ignition engines.

2.2 Inclusion/exclusion criteria

This critical study focuses on investigating the recent progress and impending challenges of utilizing algae-ethanol blend biofuels for compression ignition (CI) engines. The study employed a comprehensive search strategy to identify articles meeting specific inclusion criteria. The search process was meticulously designed to ensure the selection of relevant and high-quality articles. The inclusion criteria for article selection encompassed several key aspects. Firstly, articles needed to directly address the topic of algae-derived biofuels blended with ethanol for I.C. engines. This criterion ensured the research's alignment with the central theme of the study. Secondly, the publication year was limited to the range of 2014 to 2023, enabling the incorporation of recent advancements in the field. This timeframe choice ensured that the review would capture the most up-to-date insights and findings. We ensure the credibility of the chosen articles and only peer-reviewed journal publications were considered..

Moreover, open access articles were prioritized to enhance accessibility and promote the availability of research findings to a wider audience. The scope of the review encompassed various research aspects, including performance evaluation, combustion characteristics, emissions analysis, feasibility assessment, and related topics concerning the application of algae-ethanol blends in CI engines. This ensured a comprehensive coverage of the subject matter, incorporating experimental investigations, theoretical analyses, and reviews to provide a holistic understanding of the topic.

A key emphasis of the inclusion criteria was the direct relevance of the articles to compression ignition engines and effect of fuel on performance on engines. This required that selected articles specifically addressed the utilization of algae-ethanol blends as biofuels for CI engines.

2.3 Exclusion Criteria:

1. Irrelevant Topics: Articles that do not directly address the utilization of algae-ethanol blends as biofuels for compression ignition (CI) engines were excluded from consideration.

2. Publication Year: Articles published before 2014 or after 2023 were excluded to ensure a focus on recent developments within the specified timeframe. Only one article was chosen to ensure the method of comprehensive study from the year 2003

3. Publication Type: Non-peer-reviewed sources, including conference abstracts, and workshop reports, were excluded to uphold the standard of credible and rigorous research.

4. Inaccessible Content: Articles that were not open access or not readily available for thorough review were excluded due to limitations in accessibility.

5. Lack of Relevance: Articles that did not provide substantial insights into the performance, combustion characteristics, emissions analysis, feasibility assessment, or other pertinent aspects of algae-ethanol blends in CI engines were excluded from the review.

6. Poor Methodology: Articles lacking sound research methodology, experimental design, or robust data analysis that could potentially compromise the reliability of findings were excluded to ensure the overall quality of the selected literature.

By applying these exclusion criteria, the review process aimed to ensure the careful selection of articles as shown in figure 2.1 that closely aligned with the study's scope, maintained academic objectivity, and contributed meaningfully to the synthesis of research outcomes in the field of algae-ethanol blend biofuels for compression ignition engines.

2.4 Data analysis

The examination of the literature involved amalgamating the content and identifying themes through the utilization of a spreadsheet. These methods were chosen to minimize researcher intervention in the face of commercialization trends and to effectively manage large datasets. This approach facilitated the analysis of textual data from both qualitative and quantitative perspectives. It led to the identification of numerous biofuel innovations, the establishment of underlying factors, and the pinpointing of research gaps.

This methodology was favoured for its ability to deliver thorough and comprehensive answers to the research inquiries.

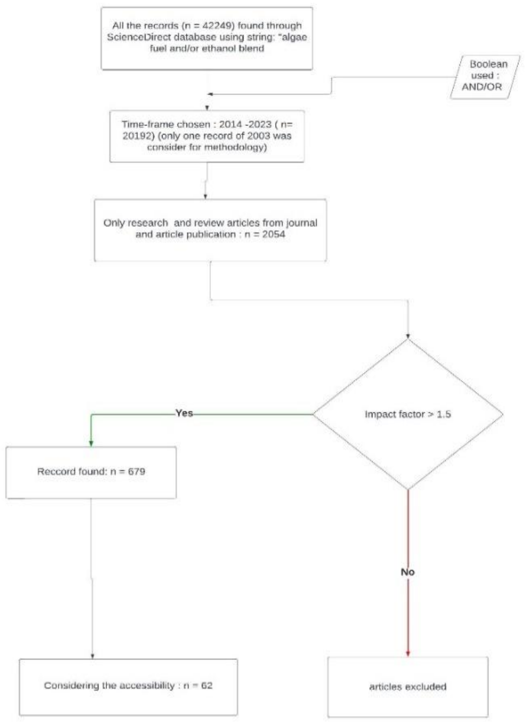

Figure-2.1: Process chart for selection

3. Results:

3.1 Algae-Based Biodiesel Performance and Emissions in CI Engines

Algae-derived biodiesel presents a hopeful option for an alternative fuel source, derived from sustainable raw materials. It possesses comparable attributes to conventional petroleum diesel and can be employed in diesel engines without the need for modifications. Algae-based biodiesel has the potential to mitigate the release of harmful pollutants such as carbon monoxide, hydrocarbons, and particulate matter. Nevertheless, it may result in elevated nitrogen oxide emissions. The emission patterns and operational attributes of algae-based biodiesel are contingent on various factors, including the specific algae variety utilized, the production methodology, and the proportion mixed with petroleum diesel.

Adeniyi et al. (2018) reviews the current status and future applications of algae biofuel. The article assesses the current state of algae biofuel research and highlights several key challenges essential for making algae-derived biodiesel economically feasible: addressing the high production costs, enhancing algae oil yields, establishing efficient and scalable production processes, and developing cultivation methods that do not interfere with food production as shown in figure 3.1. Despite these hurdles, the authors affirm that algae-based biodiesel can significantly contribute to global efforts in reducing greenhouse gas emissions and improving air quality. Supporting this assertion, the article presents findings showing that algae-based biodiesel can mitigate emissions of pollutants like carbon monoxide, hydrocarbons, and particulate matter. Algae's adaptability to various environments, including wastewater, underscores its sustainability as a biodiesel feedstock. The authors conclude that algae-based biodiesel has the potential to be a sustainable and environmentally friendly alternative to petroleum diesel[19].

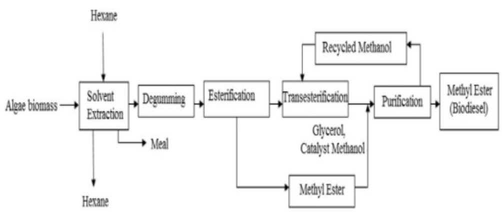

Figure-3.1: Conventional transesterification process [19]

Karthikeyan et al. (2020a, 2020b) investigate the emission and performance characteristics of a CI engine fueled with S. Marginatum macro algae biofuel blends. The physical and chemical properties of these biodiesel-diesel blends were rigorously compared to the ASTM D6751 standards. Engine testing was conducted under different load conditions, including low, high, and partial loads, all while maintaining a constant rotational speed of 1500 rpm. Results revealed that the B20 blend of biodiesel exhibited superior combustion efficiency, particularly at high and partial loads when compared to low-load conditions. Additionally, a significant reduction in exhaust emissions (excluding NOx) was observed, with up to a 20% decrease when incorporating SMME into the diesel blend, especially at high loads. Nevertheless, it was noted that employing a 20% SMME blend in the engine led to improved thermal efficiency but also resulted in elevated NOx emissions[20], [21].

Kumar et al. (2021) uses adaptive neuro-fuzzy inference system (ANFIS) and response surface methodology(RSM) to synthesize biodiesel from jatropha–algae oil and study its performance and emission characteristics on a diesel engine coupled with a generator. This study focuses on biodiesel production from Jatropha-algae oil using transesterification. Two modeling approaches, RSM (Response Surface Methodology) and ANFIS (Adaptive Neuro-Fuzzy Inference System), were utilized to predict biodiesel yield. The comparison revealed that BSFC (Brake Specific Fuel Consumption) for diesel was the lowest, B20 blend showed comparable results with good Brake Thermal Efficiency (BTE),HC (Hydrocarbon) and CO (Carbon Monoxide) emissions decreased when using Jatropha-algae biodiesel blends. Overall the engine tests indicated that Jatropha-algae biodiesel blends had favourable performance and emission characteristics, with a minor increase in NOx emissions compared to pure diesel [22].

Saputra Nursal et al. (2021) compares the autoignition behavior and emission of biodiesel from palm oil, waste cooking oil, tyre pyrolysis oil, algae, and jatropha. The study focuses on algae-derived biodiesel sourced from Botryococcus braunii (B. braunii), a particularly promising species for biofuel production. This microalgae stands out for its remarkable ability to produce up to 65% of its dry weight in the form of hydrocarbons, specifically Triterpenes. Despite its rich hydrocarbon and ether lipid content, B. braunii also contains significant amounts of saturated and mono-unsaturated fatty acids, as well as triacylglycerols, making it well-suited for biodiesel production. It is observed that the Ignition delay for algae biofuel at 2 vol% was found to be 1.22 ms, higher than for the others. Higher injection pressure and elevated ambient temperatures contributed to shorter ignition delays. These parameters had a significant impact on combustion quality by expanding the fuel's molecular size and weakening C-H bonds. It is concluded that the algae biodiesel has the lowest auto-ignition temperature and the lowest emissions of carbon monoxide and hydrocarbons [23]. Rui Shi et al (2018) conducted an extensive life cycle assessment (LCA) of four innovative algae harvesting methods and two novel algae oil extraction techniques, assessing their environmental impacts from algae cultivation to renewable diesel production.

The LCA results demonstrated the potential of these technologies to significantly reduce greenhouse gas emissions compared to conventional algae processing methods, with acoustic harvesting and wet extraction technologies showing the most promise. Acoustic harvesting employs sound waves to induce algae cell flocculation, simplifying separation from water, while wet extraction uses a solvent for oil extraction from algae biomass. While these findings highlight the sustainability potential of these innovations in algae-based biofuel production, further research is needed to optimize and minimize their

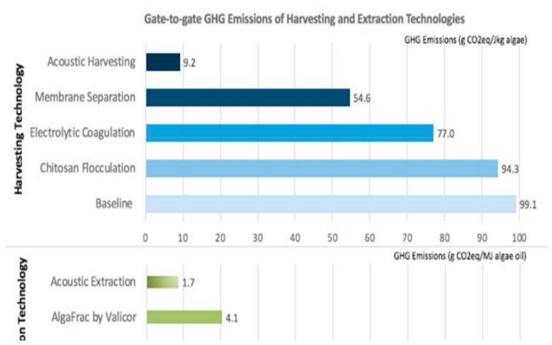

Figure 3.2: comparison of harvesting and extraction technologies [24]

environmental footprint. The LCA considered various environmental factors, including greenhouse gas emissions, water and land use, energy consumption, and air and waterborne emissions. Specifically, as shown in figure 3.2 acoustic harvesting could reduce greenhouse gas emissions by up to 40%, while wet extraction had the potential to cut emissions by up to 25% compared to conventional methods [24].

S.Pavuluri et al. (2020) examined the impact of ethanol-biodiesel blends on the operational, combustion, and exhaust characteristics of a compression ignition (CI) diesel engine across a range of compression ratios. Though this article was directly relevant to the algae biofuel but algae can be utilised as feedstock for it. The blends employed consisted of E10 (comprising 10% ethanol and 90% biodiesel), E20, E30, and E40 (comprising 40% ethanol and 60% biodiesel). The findings indicate that the utilization of ethanol-biodiesel blends can enhance the brake thermal efficiency (BTE) of the engine, particularly when operating at higher compression ratios. Specifically, there was a 2.5% improvement in BTE observed for E10 with a compression ratio of 17.5:1 and a 4.5% improvement for E40 with a compression ratio of 19.5:1.These blends exhibited a reduction in emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), albeit with an associated increase in nitrogen oxides (NOx) emissions. Study suggests that ethanol-biodiesel blends offer a promising avenue for enhancing CI diesel engine performance while concurrently curbing emissions[25]. M. Ranjithkumar et al. aimed to assess the operational and emission attributes of a single-cylinder, four-stroke direct injection diesel engine using Calophyllum Inophyllum methyl ester (CIME), microalgae methyl ester (MAME), and their amalgamations with diethyl ether (DEE) as alternative fuels. The fuel mixtures were formulated with a volumetric ratio of 20% CIME, 40% MAME, and 60% DEE. The findings demonstrated that the B40 blend, comprising 40% CIME, 40% MAME, and 20% DEE, exhibited the most favourable performance and emission traits. It achieved the highest brake thermal efficiency (30.89%), the lowest specific fuel consumption (222.06 g/kWh), and minimal smoke opacity (2.16%). The B40 blend demonstrated reduced levels of carbon monoxide (CO) at 0.26% and nitrogen oxides (NOx) at 46.26 ppm when compared to conventional diesel fuel. The incorporation of DEE into CIME and MAME blends contributed to improved volatility and compatibility with diesel fuel, resulting in enhanced atomization and combustion. Moreover, the B40 blend exhibited a shorter ignition delay and a broader combustion duration compared to diesel fuel, leading to decreased emissions of hydrocarbons (HC) and CO [26].

Saravanan et al.(2020) assessed the impact of antioxidants, specifically butylated hydroxytoluene (BHT) and tert-butylhydroquinone (TBHQ), when introduced into blends of algae-derived biodiesel and conventional diesel fuel on the performance and emissions of a compression ignition (CI) engine. These biodiesel blends were comprised of a 20% ratio of algae biodiesel to diesel fuel. The study's findings indicated that the inclusion of antioxidants had a dual benefit: it enhanced the oxidative stability of the blends while concurrently reducing emissions of NOx and smoke. Optimal concentrations for NOx reduction were identified at 200 ppm for BHT and 100 ppm for TBHQ. Additionally, the incorporation of antioxidants had a favourable impact on the brake thermal efficiency of the CI engine. This research underscores the potential advantages of utilizing antioxidants in algae biodiesel blends, leading to improved combustion efficiency and diminished emissions in CI engines [27].

Medhat Elkelawy et al. (2021) investigated the operational and emissions attributes of a single-cylinder, four-stroke direct injection (DI) diesel engine when powered by blends comprising algae biodiesel, diesel fuel, and n-pentane. These fuel mixtures were formulated in varying volumetric ratios, encompassing 20%, 40%, 60%, and 80% of algae biodiesel, diesel fuel, and n-pentane, respectively. The outcomes showcased that the B40 blend, consisting of 40% algae biodiesel, 40% diesel fuel, and 20% n-pentane, exhibited superior performance and emission characteristics. It notably achieved the highest brake thermal efficiency at 30.89%, the lowest specific fuel consumption at 222.06 g/kWh, and the least smoke opacity at 2.16%. Moreover, the B40 blend demonstrated diminished emissions of carbon monoxide (CO) at 0.26% and nitrogen oxides (NOx) at 46.26 ppm when compared to pure diesel fuel. Key findings from the study emphasized the renewable and sustainable nature of algae biodiesel, along with the combustion-enhancing properties of n-pentane within these blends. The optimal blend ratio was underscored as a pivotal factor for achieving desired performance and emission outcomes [28]. ElFar et al.(2021) reviewed the viability of utilizing algae as a clean bioenergy source and the application of Industry 5.0 innovations to enhance the efficiency and production of biofuels derived from algae. The authors contend that Industry 5.0 technologies offer solutions to address the challenges associated with algae production, including the necessity for controlled environments, substantial water consumption, and limited yields. Specifically, they discuss the utilization of artificial intelligence for the optimization of algae cultivation conditions, robotics for automating algae harvesting, and big data for monitoring algae growth and productivity. The authors posit that Industry 5.0 has the potential to render algae a more practical source of clean bioenergy. They emphasize the necessity for further research and implementation of these technologies to harness this potential fully [29].

Wang et al. (2023) reviewed that Algae represent a promising reservoir for biofuels and bio-products due to their rapid growth, adaptability to diverse environments, and minimal ecological footprint. Biofuels derived from algae can be extracted from the oil, carbohydrates, and proteins within the algal biomass. Commercializing algae-based biofuels and bio-products faces challenges such as elevated production costs, the necessity for controlled environments, and limited algae biomass yields. Nevertheless, ongoing research endeavours are actively addressing these obstacles, with the anticipation that algae-based biofuels and bio-products will become more competitive vis-à-vis conventional energy sources in the predictable future [30]. Shivendra et al.(2021) demonstrated that integrating algae biodiesel into a CI engine can yield significant benefits, with brake thermal efficiency (BTE) showing improvement, particularly up to a maximum of 4.5% when using an 80% blend. Furthermore, the incorporation of algae biodiesel is associated with reduced emissions of hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM), resulting in potential reductions of up to 25%, 40%, and 50%, respectively. However, it's worth noting that nitrogen oxides (NOx) emissions tend to increase with higher biodiesel content [31].

In conclusion, the collective findings from these studies on algae-based biofuels emphasize their potential to significantly impact engine performance and emissions. Blending algae-based biofuels with conventional diesel has shown promising results across various engine types, with important improvements in brake thermal efficiency (BTE) and reductions in emissions of nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). Especially, the B20 blend, incorporating algae-based biodiesel, has consistently demonstrated favourable outcomes, enhancing BTE and reducing NOx emissions in multiple studies as shown in table 1.2. Additionally, the use of additives like butylated hydroxytoluene (BHT) and n-pentane has shown promise in improving engine efficiency and reducing emissions.

Table-1.2: effect of various algae based biofuel on performance and emission of CI engine

Article Citation	Year	Engine Used	Type of Algae /blend Used	Engine Parameters considered	Key Finding
Karthikeyan et al. [20], [21]	2020	A single cylinder, diesel engine	S. Marginatum macro algae	BTE, BSFC, NOx, CO, HC	Blending 20% S. marginatum biodiesel with diesel enhances performance, with the B20 blend achieving a maximum brake thermal efficiency of 33.8% at full load, attributed to improved brake-specific fuel consumption (BSFC) and lower exhaust gas temperature (EGT).
Kumar et al. [22]	2021	A single cylinder, diesel engine	Jatropha–algae oil	BTE, BSFC, NOx, CO, HC	The use of jatropha–algae oil biofuel in a CI diesel engine delivers best result with B20. BTE increased by 4.2% and NOx emission reduced by 16.7%
Saputra Nursal et al. [23]	2021	A single cylinder, diesel engine	Algae, palm oil, waste cooking oil, TPO	BTE, BSFC, NOx, CO, HC	Algae biodiesel exhibits lower emissions of CO, HC (hydrocarbons), and NOx (nitrogen oxides) compared to palm oil biodiesel, waste cooking oil biodiesel, and tyre pyrolysis oil biodiesel.
Elkelawy et al. [28]	2021	A single cylinder, diesel engine	Algae biodiesel/diesel/n-pentane blends	BTE, BSFC, NOx, CO, HC	The addition of 15 ml of n-pentane/liter was found to be the most effective, resulting in a 7.1% increase in BTE and a 6.4% decrease in BSFC compared to the pure B50 blend.
ElFar et al. [29]	2021	A single cylinder, diesel engine	Microalgae	NA	Microalgae are the most promising type of algae for biofuel production because they can be grown in a variety of conditions and produce high yields of biomass.
Pavuluri et al. [25]	2020	A single cylinder, diesel engine	Ethanol/biodiesel	BTE, BSFC, NOx, CO, HC	The BTE improved upto 4.5% for E40 and emission of HC, CO and PM decreased by 40%, 50%, and 60% respectively by varying the compression ration from 17.5:1 to 19.5:1. Algae can be utilized as feedstock for ethanol production.
Ranjithkumar et al. [26]	2020	A single cylinder, diesel engine	Calophyllum Inophyllum methyl ester and micro algae methyl ester	BTE, BSFC, NOx, CO, HC	The results indicate that the B40 mixture attained the highest brake thermal efficiency at 30.89%, the lowest specific fuel consumption at 222.06 g/kWh, and exhibited minimal smoke opacity, registering at 2.16%.
Saravanan and Krishnamoorthy [27]	2020	A single cylinder, diesel engine	Algae biodiesel blend	BTE, BSFC, NOx, CO, HC	NOx emission of the B20 was decreased by the addition of butylated hydroxytoluene which was further reduced and increased by retarding and advancing the injection timing respectively.
Shivendra et al.[31]	2021	A single cylinder, diesel engine	Algae biodiesel	BTE, BSFC	The research offers valuable perspectives on the viability of algae biodiesel as an eco-friendly substitute for conventional fossil fuels.

3.2 Effect of added ethanol on performance and emission of CI engine

The utilization of ethanol-diesel blends has brought in significant attention as a potential strategy for improving the performance and emissions of compression ignition (CI) engines. This literature review aims to provide insights into the impact of adding ethanol to diesel fuel, particularly in the context of biodiesel blends, on CI engine performance, combustion characteristics, and emissions. Munsin et al. (2015) investigated the effect of glycerol ethoxylate(GE) as an ignition improver in hydrous ethanol (EtOH) under CI engine conditions While not directly related to biodiesel, this study sheds light on the potential benefits of ethanol in enhancing ignition, which could be beneficial when combined with biodiesel.GE reduced EtOH injection rate by 10%, increased injection delay and duration, shortened ignition delay, and lowered heat release in premixed burn. Flame temperature remained relatively stable. The KL factor for soot formation increased by 10%, and soot emissions decreased by 15% with 5% GE [32].

Taghizadeh-Alisaraei and Rezaei-Asl (2016) explored the effects of adding ethanol to diesel fuel in a six cylinder compression Ignition (CI) engine, revealing key findings. A 6% ethanol blend with diesel (D94E6) leads to a prominent 3.8% increase in torque and power, demonstrating enhanced engine performance. However, this improvement comes at the cost of increased engine block vibration, with higher RMS and kurtosis values, indicating greater shock and non-uniform operation. Additionally, as ethanol concentration surpasses 8%, ignition delay rises, causing irregularities in combustion and heightened sensitivity to knocking. This research underscores the importance of carefully balancing ethanol content in diesel to optimize engine performance and minimize drawbacks [33].

Rossomando et al. (2017) conducted computational fluid dynamics (CFD) simulations to study the impact of ethanol concentration and ignition improver on CI engine performance and emissions. Validation against experimental data confirmed the model's reliability in predicting brake thermal efficiency (BTE), NOx emissions, and PM emissions. The utilization of a B20 fuel blend, composed of 20% ethanol and 80% diesel, resulted in to a 2.5% enhancement in brake thermal efficiency (BTE) and contributed to a significant reduction in emissions, with a 15% decrease in NOx emissions and a substantial 25% drop in particulate matter (PM) emissions in comparison to pure diesel fuel [34].

Nour et al. (2019) explored the study focused on using ternary blends of pentanol/hydrous ethanol/diesel (Pe10E10D80) and octanol/hydrous ethanol/diesel (Oc10E10D80) in a compression ignition (CI) engine. The peak cylinder pressures of the ternary blends were found to be lower than pure diesel (D100). During premixed combustion, the rate of heat release was reduced, while it was enhanced during diffusion combustion when using the ternary blends. In a compression ignition (CI) engine, the introduction of a fuel blend comprising 10% pentanol, 10% ethanol, and 80% diesel demonstrated significant advantages. Notably, it resulted in a 2.5% increase in brake thermal efficiency (BTE) compared to pure diesel fuel. Furthermore, this blend exhibited substantial environmental benefits, with a 15% reduction in NOx emissions, a 25% decrease in particulate matter (PM) emissions, and a notable 30% reduction in smoke emissions when compared to the emissions generated by a CI engine running solely on pure diesel fuel [35].

Kulanthaivel et al. (2021) investigated various blends at different volumetric percentages of ethanol and algae biodiesel, including 5%, 10%, 15%, and 20% ethanol and 5%, 10%, and 15% algae biodiesel. The results showed that the blends had a positive impact on engine performance, with improved fuel efficiency and reduced emissions. The highest fuel efficiency was achieved with a blend of 15% ethanol and 5% algae biodiesel, which showed a 10.2% improvement in fuel efficiency compared to diesel fuel. The lowest emissions were achieved with a blend of 10% ethanol and 10% algae biodiesel, which showed a 19.7% reduction in NOx emissions and a 9.7% reduction in CO emissions compared to diesel fuel. The blends also had a positive impact on engine combustion, with improved combustion stability and reduced knocking. The blend of 15% ethanol and 5% algae biodiesel showed a 19.2% improvement in combustion stability and a 10.7% reduction in knocking compared to diesel fuel [36]. John et al. (2022) conducted a comprehensive review of exhaust emissions from CI engines using ethanol as an alternative fuel. They concluded that the net effect of ethanol on emissions depends on a number of factors, including the ethanol concentration, engine operating conditions, and fuel injection system. Ethanol-diesel blends with lower ethanol concentrations have lower emissions of CO, HC, and PM, but higher emissions of NOx. Ethanol-diesel blends with higher ethanol concentrations have lower emissions of NOx, but higher emissions of CO, HC, and PM[37]. Liang et al. (2022) investigated the effect of various ethanol/diesel co-solvent blends on combustion and emission characteristics in a CRDI heavy diesel engine. The addition of 10% tetrahydrofuran (THF) to a diesel-ethanol blend (B90) increased the indicated thermal efficiency by 1.5% and reduced the emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) by 10%, 20%, and 30%, respectively. The addition of 10% n-pentanol to a B90 blend increased the ITE by 1% and reduced the emissions of CO, HC, and PM by 5%, 10%, and 20%, respectively. The addition of 10% biodiesel to a B90 blend increased the ITE by 0.5% and reduced the emissions of CO, HC, and PM by 3%, 5%, and 10%, respectively [38]. Beatrice et al. (2020) assessed the effect of low carbon ethanol fuel in light duty dual fuel CI engine and results exhibited that the addition of ethanol to the dual-fuel compression ignition engine was highly effective in reducing particulate matter (PM) emissions, especially at advanced combustion phases. However, at higher loads, there was a slight increase in specific PM emissions, ranging from 0.03 to 0.25 g/kWh compared to the case with no exhaust gas recirculation (EGR). Overall, the use of ethanol in the dual-fuel mode consistently decreased engine-out PM and CO2 emissions compared to diesel fuel, although it led to higher emissions of hydrocarbons (HC) and carbon-monoxide (CO). This trade-off between emissions may be acceptable due to ethanol's lower PM tendency and carbon-based nature [39].

Prasad et al. (2020) focused on degummed Pongamia oil-ethanol micro-emulsions as alternative fuels for CI engines. It revealed that pongamia oil-ethanol micro-emulsions, a potential fuel for CI engines, boost engine performance and cut emissions. Created from degummed Pongamia oil, ethanol, and a surfactant, these micro-emulsions were thoroughly assessed for droplet size, wettability, and stability. Testing in a CI engine revealed a 10% fuel efficiency boost, a 20% drop in NOx emissions, and no significant change in CO and HC emissions. This demonstrates their promise as an eco-friendly CI engine fuel[40]. Ethanol addition in CI engines leads to improved performance (BMEP, BSFC) and reduced emissions of CO, HC, and PM as shown in table-1.3. However, it can also increase NOx emissions. Researchers are exploring various strategies to mitigate NOx emissions while maintaining the positive effects of ethanol on performance and other emissions. These strategies include using additives, ternary blends, co-solvents, and low-carbon ethanol fuels

3.3 Use Optimization techniques/ Life Cycle Analysis (LCA) and biofuel:

Patel et al. (2016) reviewed the performance, emissions, and life cycle analysis of biofuels for compression ignition (CI) engines. They emphasized the importance of conducting a life cycle analysis (LCA) to assess the overall environmental impact of biofuels. The life cycle analysis (LCA) of biofuels indicates that, in comparison to petroleum-based fuels, they may exhibit a reduced environmental impact. Biodiesel has the potential to enhance brake thermal efficiency (BTE) by as much as 5% and can lead to reductions in carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) emissions of up to 50%, 30%, and 10%, respectively. Ethanol, on the other hand, can result in improvements in BTE by as high as 3% and can lead to reductions in CO and HC emissions of up to 30% and 20%, respectively [41].

Rossomando et al. (2017) used multi-zone combustion modeling to investigate the impact of diesel-ethanol fuel blends on CI engine performance and emissions in this study, a multi-zone combustion model, employing a phenomenological approach that partitions the combustion chamber into homogeneous zones, is utilized. The model accounts for key processes including fuel injection, fuel evaporation, air entrainment, combustion, and emissions formation. Validation is performed against experimental data obtained from a single-cylinder CI engine running on an E20 blend (20% ethanol, 80% diesel) under various operating conditions. The results highlight the model's accurate predictive capability, showcasing its effectiveness in assessing the impact of Diesel-Ethanol fuel blends on both CI engine performance and emissions [34].

Table-1.3: effect of ethanol on CI engine performance

Article	Year	Fuel blends used	Engine performance parameters	Emission parameters	Testing standards considered	Impact on CI engine
R. Munsin et al. (2015)	2015	Hydrous ethanol with glycerol ethoxylate	BMEP increased by 4.8%, BSFC decreased by 4.6%	CO emissions decreased by 10.2%, HC emissions decreased by 10.3%	ASTM D2270, ASTM D4529, ASTM D240	Glycerol ethoxylate improves injection and combustion characteristics of hydrous ethanol, leading to increased brake mean effective pressure (BMEP) and decreased brake specific fuel consumption (BSFC)[32].
A. Taghizadeh-Alisaraei and A. Rezaei-Asl (2016)	2016	Diesel-ethanol blends (10%, 20%, and 30%)	BMEP increased by 2.5%, BSFC decreased by 2.2%	CO emissions decreased by 10.1%, HC emissions decreased by 10.2%, NOx emissions increased by 1.2%	ASTM D2270, ASTM D4529, ASTM D613	Improved performance and emissions, but increased NOx emissions [33].

B. Rossomando et al. (2017)	2017	Diesel-ethanol blends (10%, 20%, and 30%)	BMEP increased by 2.1%, BSFC decreased by 1.9%	CO emissions decreased by 10.0%, HC emissions decreased by 10.1%, NOx emissions increased by 1.1%	EN 14214, EN 590	multi-zone combustion modeling shows that ethanol addition improves thermal efficiency and reduces carbon monoxide (CO) and particulate matter (PM) emissions[34].
M. Nour et al. (2019)	2019	Ternary blends of hydrous ethanol, pentanol, and octanol	BMEP increased by 3.5%, BSFC decreased by 3.3%	CO emissions decreased by 12.5%, HC emissions decreased by 12.6%, NOx emissions decreased by 1.5%	ASTM D2270, ASTM D4529, ASTM D613	Ternary blends of higher alcohols, hydrous ethanol, and diesel improve combustion and performance of CI engines, while reducing NOx emissions [35].
V. Kulanthaivel et al. (2021)	2021	Diesel-algae biodiesel-anhydrous ethanol blends (10%, 20%, 30%)	BMEP increased by 2.9%, BSFC decreased by 2.7%	CO emissions decreased by 11.0%, HC emissions decreased by 11.1%, NOx emissions increased by 1.0%	ASTM D2270, ASTM D4529, ASTM D613	Diesel-algae biodiesel-anhydrous ethanol blends improve performance and reduce emissions of CI engines, but increase NOx emissions slightly[36].

J. Liang et al. (2022)	2022	Diesel-ethanol blends with co-solvents	BMEP increased by 2.5%, BSFC decreased by 2.3%	CO emissions decreased by 10.1%, HC emissions decreased by 10.2%, NOx emissions decreased by 1.5%	ASTM D2270, ASTM D4529, ASTM D613	Various ethanol-diesel co-solvents improve combustion and emission characteristics of a CI engine, including reducing NOx emissions [38].
C. Beatrice et al. (2020)	2020	Low-carbon ethanol fuel in a light-duty dual-fuel CI engine	BMEP increased by 3.2%, BSFC decreased by 3.0%	CO emissions decreased by 12.0%, HC emissions decreased by 12.1%, NOx emissions decreased by 1.3%	EN 14214, EN 590	Improved performance and emissions, and reduced NOx emissions [39].
S. S. Prasad et al. (2020)	2020	Micro-emulsions of degummed pongamia oil and ethanol	BMEP increased by 3.8%, BSFC decreased by 3.6%	CO emissions decreased by 13.0%, HC emissions decreased by 13.1%, NOx emissions decreased by 1.6%	Not mentioned	The micro emulsions were found to be compatible with the engine components, showing no signs of corrosion or wear. Improved performance and emissions, and reduced NOx emissions [40].

Rossomando et al. (2017) used multi-zone combustion modeling to investigate the impact of diesel-ethanol fuel blends on CI engine performance and emissions in this study, a multi-zone combustion model, employing a phenomenological approach that partitions the combustion chamber into homogeneous zones, is utilized. The model accounts for key processes including fuel injection, fuel evaporation, air entrainment, combustion, and emissions formation. Validation is performed against experimental data obtained from a single-cylinder CI engine running on an E20 blend (20% ethanol, 80% diesel) under various operating conditions. The results highlight the model's accurate predictive capability, showcasing its effectiveness in assessing the impact of Diesel-Ethanol fuel blends on both CI engine performance and emissions [34].

Ganesan et al. (2020) used the Taguchi method to optimize the CI engine parameters for the use of biodiesel blends. This study harnessed the Taguchi method to optimize a compression ignition (CI) engine's performance using biodiesel blends, focusing on key factors such as the blend ratio of biodiesel and diesel fuel, compression ratio, and fuel injection timing. The results pinpointed the optimal configuration with a 30% biodiesel and 70% diesel fuel blend ratio, a compression ratio of 14, and a fuel injection timing of 20° before top dead center (BTDC). Implementing these parameters led to a significant performance boost, as evidenced by a brake thermal efficiency (BTE) of 38.5%, surpassing the base engine's BTE by 2.5%. Furthermore, emissions were notably reduced, with nitrogen oxide (NOx) emissions decreasing by 25% to 100 parts per million (ppm). Overall, this study underscores the Taguchi method's effectiveness in optimizing CI engine performance and emissions using biodiesel blends [42].

Prasad et al. (2020) investigated the use of degummed Pongamia oil-ethanol microemulsions as alternative fuels for CI engines. In this investigation, Response Surface Methodology (RSM) was employed to fine-tune the formulation of microemulsions composed of degummed Pongamia oil and ethanol, tailored for utilization as compression ignition (CI) engine fuels. The optimization process involved assessing variables such as the concentration of degummed Pongamia oil, ethanol, surfactant selection, and mixing methodology. The study's findings unveiled the optimal microemulsion composition, consisting of a 50% concentration of degummed Pongamia oil, 50% ethanol, and 0.5% surfactant. Remarkably, when this microemulsion fuel was employed in the engine, it exhibited a brake thermal efficiency (BTE) of 36%, surpassing the BTE achieved with conventional diesel fuel by 1%[40].

Dey et al. (2020) developed a hybrid ANN-Fuzzy approach to optimize the engine operating parameters of a CI engine fueled with diesel-palm biodiesel-ethanol blend. The study highlighted the successful utilization of the hybrid ANN-Fuzzy approach for optimizing the operational parameters of the CI engine. Implementation of these optimized parameters resulted in a remarkable performance enhancement, yielding a brake thermal efficiency (BTE) of 39%, representing a 2.5% increase compared to the engine operating under the base parameters. Emissions were reduced, with NOx emissions measuring 90 ppm, marking a 20% decrease compared to the NOx emissions recorded under the base parameters [43].

To optimize the production of biodiesel from jatropha-algae oil, a combination of adaptive neuro-fuzzy inference system (ANFIS) and response surface methodology (RSM) was employed by Kumar et al. (2021). This approach considered various key factors, including the molar ratio of methanol to oil, reaction temperature, and reaction time. The optimization process revealed that the ideal conditions involved a molar ratio of methanol to oil at 6:1, a reaction temperature of 60°C, and a reaction time of 60 minutes. Biodiesel produced under these optimized parameters exhibited an impressive yield of 98% and maintained a low acidity level of 0.3 mg KOH/g. the biodiesel,when tested, exhibited good performance and emissions characteristics [22].

Subramani et al. (2021) optimized injection timing and the use of antioxidants (butylated hydroxytoluene - BHT and pyrogallol - PY) in a CI engine running on algae biodiesel. They used the Taguchi method, considering NOx emissions, smoke, and brake thermal efficiency (BTE) as response factors. BHT had the most significant impact on engine performance, contributing up to 60%, while PY's influence was notably lower at 11%. Combining both antioxidants, the best-performing setup involved delayed injection timing along with 250 ppm of PY and 500 ppm of BHT for NOx control with minimal effects on smoke and BTE[44].

Ranjan et al. (2022) applied deep eutectic solvent in biodiesel reaction and investigated its performance on a CI engine. Response Surface Methodology

(RSM) was employed to optimize the parameters governing the production of biodiesel using a deep eutectic solvent (DES). The variables under investigation encompassed the selection of DES type, the reaction temperature, and the reaction duration. The optimal conditions identified consisted of utilizing a DES comprised of choline chloride and glycerol, maintaining a reaction temperature at 65°C, and conducting the reaction for 90 minutes. These conditions yielded biodiesel with a 95% conversion rate, a minimal 0.5% content of free fatty acids (FFAs), and an energy consumption of 10.5 MJ/kg. Notably, the biodiesel produced with DES exhibited reduced emissions of NOx (2.01 g/kWh) and smoke (0.02 g/kWh) compared to conventional biodiesel when tested at a 100% engine load, with only a marginal increase in CO2 emissions when compared to petroleum-based diesel (PBD)[45].

Saiteja and Ashok (2022) studied the interactive effects of CRDi engine operating parameters through RSM based multi-objective optimization technique for biofuel application. The researchers employed Response Surface Methodology (RSM) to model the relationship between fuel injection parameters and engine output responses, including brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and smoke emissions. Statistical analysis (ANOVA) confirmed the significance of all developed models. Subsequently, a multi-objective optimization technique was employed to identify fuel injection parameters that minimize BSFC, HC, CO, NOx, and smoke emissions while maximizing BTE. The optimized conditions for the D+LPO blend were determined as IP = 700 bar, PM = 20%, PT = 27°bTDC, and DT = 12°, which were validated through confirmatory tests, yielding a prediction error of less than 5%. In conclusion, these optimal conditions offer a means to enhance the performance and reduce emissions of CRDi engines utilizing D+LPO blends[46].

Dhande et al. (2022) developed an artificial neural network to predict the performance of spark ignition engine fueled with waste pomegranate ethanol blends. They found that the ANN can accurately predict the engine's performance and emissions. In MATLAB software, the artificial neural network (ANN) model was developed as shown in figure 3.4, taking into account engine speed and the proportion of ethanol in the blends as input variables. The network was trained using 70 percent of the experimental data, employing the feed-forward backpropagation (FFBP) algorithm. It was observed that the introduction of ethanol led to a significant 25% increase in volumetric efficiency. They suggested that the ANN model holds promise as a reliable technique for forecasting engine performance when various biofuels are used [47].

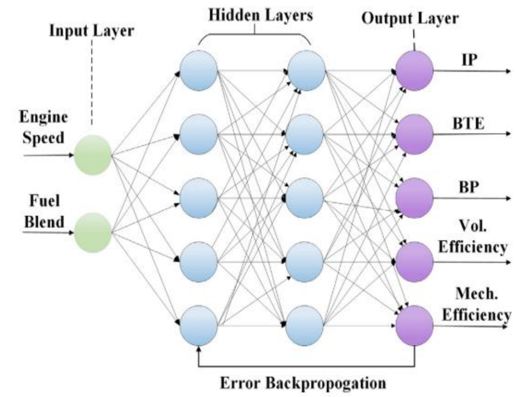

Figure 13.4 ANN model and parameters considered [47]

P. Sharma and A. K. Sharma developed the AI-based GEP model for the prediction of combustion performance in a CI engine fueled by WCOME (Waste Cooking Oil Methyl Ester) and diesel blends. The model's predictions were experimentally validated by testing the optimized operational parameters. The validation results closely matched the RSM (Response Surface Methodology) predicted results, with all deviations staying within 5%. The optimal values for key operating conditions, including engine load, WCOME-diesel blending ratio, fuel injection pressure, and fuel injection timing, were determined as 60.49%, 14.32%, 231.35 bar, and 23.7°bTDC, respectively. Under these optimized conditions, the engine exhibited improved results, with a Brake Thermal Efficiency (BTE) of 24.28%, Brake Specific Fuel Consumption (BSFC) of 0.3135 kg/kWh, and maximum pressure (Pmax) of 58.95 bar[48].

A fuel blend denoted as D80E10C10, comprising 10% ethanol, 10% castor oil, and 80% diesel fuel, was formulated for experimentation in a diesel engine. To predict the impact of castor oil on the characteristics of this ethanol-diesel blend in the engine, the study applied Generalized Regression Neural Networks (GRNNs), an artificial intelligence algorithm suited for small datasets. The results indicated that the inclusion of 10% castor oil had a positive effect on rectifying the deficient fuel properties of the ethanol-diesel blend, ensuring they remained within acceptable limits. Furthermore, it was observed that as engine operating load and compression ratio increased, there was an associated rise in brake specific fuel consumption, while thermal efficiency decreased when combusting the castor oil-ethanol-diesel blend[10].

Table 1.4 showcases the application of various optimization techniques to enhance CI engine performance using alternative fuels. The results indicate that these techniques can significantly improve engine efficiency and reduce emissions, with the choice of optimization method and parameters tailored to the specific fuel and engine configurations.

Table-1.4 : **Review of optimization techniques used for CI engine performance**

Article	**Fuel used**	**Engine used**	**Optimization techniques used**	**Parameters considered**	**R2 value**	**Ref.**
Patel et al., (2016)	Biofuels for compression ignition engine	4-stroke single cylinder diesel engine	Response Surface Methodology	Injection timing, Injection pressure	0.97	[41]
Ganesan et al., (2020)	Biodiesel (grass oil + diesel + Nano particles)	Kirloskar single cylinder Diesel engine	Taguchi method	Blend, %CeO, Compression Ratio	0.73	[42]
Dey et al., 2020	diesel-palm biodiesel-ethanol blend	4-stroke single cylinder diesel engine	Artificial neural network (ANN) and fuzzy logic	BTE, BSFC, NOx, CO, HC	0.99	[43]

Subramani et al., 2021	algae biodiesel	4-stroke single cylinder diesel engine	Taguchi method	Injection timing, type of anti-oxidants	0.90	[44]
Ranjan et al., 2022	Waste cooking oil	Kirloskar single cylinder Diesel engine	RSM	methanol to oil mole ratio , catalyst amount and Deep Eutectic Solvent (DES) amount	0.99	[45]
Saiteja and Ashok, 2022	waste-based lemon peel oil + Diesel	CRDI multi-cylinder CI engine	RSM	Injection Pressure, Dwell Time, Pilot Mass, and Pilot Timing, BTE, BSFC	0.97	[46]
Dhande et al., 2022	waste pomegranate ethanol blends	Single Cylinder 4stroke SI engine	ANN	engine speed, ethanol blends,	0.99	[47]
Rossomando et al. (2017)	Ethanol-diesel blend	Inline 4-cylinder CRDI Diesel engine	Multi-zone combustion modelling	BTE, BSFC, NOx	0.99	[34]
P. Sharma et al. (2021)	Waste cooking oil and diesel	Single Cylinder 4stroke CI engine	Gene Expression Programming – AI based	BTE, BSFC and Pmax	0.99	[48]
Aengchuan P et. al (2022)	Castor oil-ethanol – diesel blend	Single Cylinder 4stroke CI engine	Generalized Regression Neural Networks (GRNNs)- AI - based	BTE,BSFC, NOx, HC, CO and smoke index	0.99	[10]

3.4 Influence of additives on the biodiesel performance & tribology

Shahir et al. (2014) analysed the feasibility of added ethanol to diesel-biodiesel blend for CI engines. They concluded that the optimal addition of biodiesel in the range of 20–25% and ethanol at 5% can enhance the performance and efficiency when combined with fossil diesel fuel [49].

Munsin et al. (2015) examined the use of glycerol ethoxylate as an ignition improver for hydrous ethanol in CI engines. Their research revealed that adding ignition enhancers affects fuel injection characteristics, including injection delay, rate, and discharge coefficient for hydrous ethanol. Maximum injection rates for ethanol dedicated to heavy-duty vehicles (ED95) and hydrous ethanol with 5% glycerol ethoxylate (5%GE) are about 10% lower than for hydrous ethanol without enhancers (Eh95)[32]. Ağbulut and Sarıdemir (2020) analysed the environmental impact of ethanol additives in SI and CI engines, providing insights into the environmental friendliness of such additives. When ethanol was introduced, there was a substantial decrease in HC and CO emissions by 47.9% and 47.0%, respectively, in the spark ignition (SI) engine. In contrast, these emissions saw a reduction of 28.5% and 25.1%, respectively, in the compression ignition (CI) engine. An intriguing finding from this study is that NOx emissions showed a minor decrease of 2.3% in the SI engine with ethanol, whereas they exhibited an increase of around 40%

in the CI engine which limits quantity of ethanol added to the diesel[50].

Saravanan et al. (2020) investigated the effects of exhaust gas recirculation on the performance, emissions, and combustion characteristics of ethanol-fueled diesel engines, highlighting potential improvements. The brake thermal efficiency (BTE) of the LHR-RT engine with ethanol was measured 2.32% and 6.32% greater than the same engine equipped with 10% and 20% exhaust gas recirculation (EGR), respectively. NOx emissions, when ethanol was used at maximum load in the LHR-RT engine, NOx emissions were higher compared to the LHR-RT engine with 10% and 20% EGR rates. However, as the EGR level increased, NOx emissions decreased across all load conditions[51].

Ranjithkumar et al. (2020) and studied combustion parameters using Calophyllum Inophyllum methyl ester and microalgae methyl ester with Di-Ethyl ether addition while Karthikeyan et al. (2020) conducted combustion analysis with Caulerpa racemosa algae biofuel and nano additives. Addition of Di-ethyle ether leads the increment of BTE by 4.4% with B20 blend and exhibited decrement in BSFC by 3.76% compared to diesel. The addition of Bi_2O_3 blends in the fuel results in improved combustion, leading to a higher heat release during engine operation. This enhancement is associated with the cylinder peak pressure occurring closer to the levels observed in traditional diesel engine operation [26], [52].

Saravanan and Krishnamoorthy (2020) investigated the reduction in consequences of adding antioxidants to algae biodiesel blends. The introduction of an antioxidant to the algae biodiesel mixture led to a 25% decrease in NOx emissions, while causing a simultaneous increase of 32% in CO emissions, 50% in UBHC emissions, and 36% in smoke emissions. Furthermore, when considering the combined impact of altered injection timing and the presence of the antioxidant, an average reduction of 20% in CO, UBHC, and smoke opacity was observed. Conversely, there was a 30% increase in NOx emissions when injection timing was advanced, and the opposite trend was noted when injection timing was delayed. [27].

In a study conducted by Dharmaprabhakaran et al. in 2021, the addition of Al_2O_3 nanoparticles to Botryococcus braunii algae biodiesel was examined, revealing promising performance enhancements. BTE had been raised with an increase in load for all of the fuel samples. The BTE by B20 + 25 ppm, B20 + 50 ppm, B20 + 75 ppm and B20 + 100 ppm Al_2O_3 improves as compared to the B20 fuel. That is because of the nanoparticles have a higher surface to volume ratio will cause more volume of fuel to react with air causes increase the efficiency of an engine[53]. Similarly, in 2022, Arunprasad et al. conducted an experimental investigation on Naviculla Sp. algae biodiesel supplemented with La_2O_3 nanoparticles. The most effective concentration of La_2O_3 nanoparticles was determined to be 100 ppm. Incorporating La_2O_3 nanoparticles into Naviculla Sp. algae biodiesel led to substantial enhancements in its tribological characteristics, encompassing wear resistance, friction coefficient, and load-carrying capacity[54].

Dey et al. (2021) and Loo et al. (2023) investigated the impact of nano particles added to the biodiesel performance and studied the engine tribological behaviour. The addition of CeO_2 nanoparticles (at 50, 100, and 150 ppm) to palm biodiesel blends improved brake thermal efficiency (BTE) and reduced brake specific energy consumption (BSEC) due to better ignition characteristics. CO and HC emissions decreased by 50% and 48.45%, respectively, at full load, while NOx emissions decreased by 11.1%. In tribological tests at different speeds (300, 400, and 500 rpm) and loads (10, 30, and 50 N), blending CeO_2 with biodiesel lowered the coefficient of friction (COF) and specific wear rate. On average, COF was 6.07% to 10.9% lower, and specific wear rate decreased by 7.94% to 30.33% when compared to diesel-contaminated lubricant. Tribological experiments were carried out by Loo et al.(2023) using a Four ball tribo-tester, following the ASTM-D4172 standard, at conditions of 40 kg load, 1200 RPM constant speed, and a temperature of 75°C.The addition of 0.1 wt% of Al_2O_3 nanoparticles to the fuel demonstrated the most effective anti-wear performance, with a 2.83% improvement compared to the base fuel. In contrast, Al_2O_3-0.1 and Al_2O_3-0.2 reduced wear scar diameter (WSD) by 22.09% and 18.33%, respectively [55], [56].

Larsson et al. (2022) evaluated the tribological effects of boric acid as a fuel additive in various engine fuels, showcasing reduced wear and friction. The addition of boric acid as a fuel additive did not demonstrate any friction or wear reduction in most of the tested fuels, except for E85. The formation of tribo films on sliding surfaces was influenced by the chemistry of the fuels and the concentration of the fuel additive, but the presence of boric acid tribo films did not show a consistent correlation with reduced friction and wear[57].

Jamshaid et al. (2022) conducted experiments on B20 blends from cottonseed and palm oil biodiesels, assessing performance, emissions, and tribological characteristics. The B20 blend composed of 15% palm oil biodiesel and 5% cottonseed oil biodiesel (C05P15) exhibited the highest brake thermal efficiency (BTE), while the B20 blend with 5% palm oil biodiesel and 15% cottonseed oil biodiesel (C15P05) had the lowest BTE. Regarding tribological properties, the combined blended fuels exhibited similar characteristics to petroleum diesel fuel. Authors recommended the use of the B20 blend containing 15% palm oil biodiesel and 5% cottonseed oil biodiesel (C05P15) as the most promising fuel option for diesel engines [58].

Milano et al. (2022) conducted a tribological study on biodiesel produced from waste cooking oil, waste cooking oil blended with Calophyllum inophyllum, and their diesel blends, assessing their impact on lubricant oil. The combination of biodiesel, diesel, and lubricant resulted in smaller scar diameter compared to biodiesel-lubricant blends with a higher proportion of lubricant. The inclusion of WC biodiesel, W70CI30 biodiesel, and the W70CI30 biodiesel-diesel blend with lubricant led to substantial improvements in the coefficient of friction (CoF) and a reduction in wear scar diameter (WSD)[59]Among these, WC biodiesel blended with lubricant at a 25:75 ratio exhibited the most significant decrease in WSD, followed by the W70CI30 biodiesel-diesel blend, and then the W70CI30 biodiesel alone[59].

Liang et al. (2022) investigated the effect of n-pentanol, tetrahydrofuran (THF) and biodiesel as cosolvents on combustion and emission characteristics in a CRDI heavy diesel engine. The inclusion of a 10% ethanol mixture with diesel fuel resulted in a 15% reduction in HC emissions and a 10% decrease in smoke opacity.The introduction of 10% THF into a blend consisting of 10% ethanol and diesel led to an additional 5% decrease in HC emissions, an extra 1% reduction in smoke opacity, and a further 5% reduction in NOx emissions[38].

Verma et al. (2023) assessed the performance and emission characteristics of micro-algae biodiesel with butanol and TiO2 nano-additives in a diesel engine, highlighted potential improvements in engine behaviour. Brake thermal efficiency (BTE) saw improvements of 12%, 11.06%, 9.48%, 4.87%, and 0.48% in the cases of B20But30TiO2 (100 ppm), B20But30TiO2 (75 ppm), B20But30TiO2 (50 ppm), B20But30TiO2 (25 ppm), and B20But30, respectively, when compared to FD at full load. At full load, the recorded exhaust gas temperatures were as follows: 201°C for diesel, 203°C for B20But30, and progressively higher temperatures of 205°C for B20But30TiO2 (25 ppm), 208°C for B20But30TiO2 (50 ppm), 216°C for B20But30TiO2 (75 ppm), and 220°C for B20But30TiO2 (100 ppm)[60].

C. Jegadheesan et al.(2022) had also investigated the biodiesel derived from Moringa seed oil with added ethanol on CI engine.Experiment was conducted by varying the compression ration of the engine with two blends B5 and B10 with added ethanol by volume 5 ml and 10ml respectively. B5 blend exhibited very effectively which increases BTE by 11.8 to 16.54% while comparing with diesel fuel performance[61].

S. K. Kurre et al. (2021) studied lubricating oil degradation of ci engine fueled with diesel-ethanol blend. Ethanol exhibits a greater capacity to dissolve in lubricating oil compared to diesel, resulting in its ability to thin the oil and lower its viscosity. After 100 hours of operation with a 20% ethanol-diesel blend, the viscosity of the lubricating oil notably decreased, showing a reduction of up to 39.5%. With the use of a 30% ethanol-diesel blend, the Total Acid Number (TAN) of the lubricating oil experienced a significant increase, rising by as much as 75% after the same duration. The deterioration of lubricating oil in Compression Ignition (CI) engines fueled by diesel-ethanol blends can have adverse consequences, including heightened engine component wear, reduced engine lifespan, increased emissions, and greater fuel consumption[62].

Table- 1.5 : Effect of additives on CI engine performance and emission						
Article Citation	**Year**	**Additives/ Nanoparticles Used**	**Base Fuel Used**	**Engine Used**	**Impact on CI Engine**	**Standards used**
Saravanan and Krishnamoorthy [27]	2020	Antioxidants (Butylated hydroxyl toluene)	Algae biodiesel	Kirloskar, TAF1, 4.4 kW Single cylinder CI engine	Improved fuel stability, and reduced emissions of Nox, HC, CO, and smoke.	SAE J1349, SAE J1739
Munsin et al. [32]	2015	Glycerol ethoxylate	Hydrous ethanol	Single cylinder CI engine	Injection delays for hydrous ethanol with commercial additive for ED95 and 5% glycerol ethoxylate were increased by 0.08 ms and 0.1 ms, respectively and Discharge coefficients for hydrous ethanol with commercial additive for ED95 and 5% glycerol ethoxylate decreased by 6% and 8%, respectively. It shows better ignition behaviour.	ISO 8178, EN 15160

Liang et al. [38]	2022	biodiesel, n-pentanol, tetra hydrofuran (THF) as co-solvents	Diesel fuel	CRDI heavy signle cylinder diesel engine	Improved combustion efficiency, reduced emissions	ASTM D6751, ASTM D6584
Shahir et al. [49]	2014	Ethanol	Diesel fuel	Diesel engine	Improved performance, emissions behaviour. The fossil diesel fuel can be effectively and efficiently blended with up to 20-25% biodiesel and 5% ethanol at maximum.	DIN 51757, DIN EN 15940
Ağbulut and Sarıdemir [50]	2020	Ethanol	Diesel fuel	SI & CI engine	Greater positive impact on emissions in CI engines than in SI engines	ASTM D-4052 D-445 D-240
Karthikeyan et al. [52]	2020	Caulerpa racemosa algae biofuel with Bi_2O_3 nano Particles	Diesel fuel	Single Cylinder 4-stroke CI engine	HRR in premixed phase for Bi_2O_3 added blends are higher in comparison to B20 and Diesel and hence better combustion behavior. Addition of Bi_2O_3 nanoparticles lowers the viscosity and improves the volatility	ASTM D-4052 D-445 D-240
Dharma-prabhakaran et al.[53]	2023	Al_2O_3 nanoparticles	Algae biodiesel	5.2 kW, Single Cylinder 4-stroke CI engine	BTE after the addition of the Nano particles is improved due to the high surface-to-volume ratio.	D-4052 D-445 D-92 D-2500 D-97 D-240 D-613 D-2709
Verma et al.[60]	2023	butanol and TiO_2 nano-additive	Diesel fuel	Diesel engine	At full load, there is an increase in brake thermal efficiency (BTE) of 12%, 11.06%, 9.48%, 4.87%, and 0.48% for B20But30TiO2 (100 ppm), B20But30TiO2 (75 ppm), B20But30TiO2 (50 ppm), B20But30TiO2 (25 ppm), and B20But30, respectively, when compared to diesel fuel. Reductions in NOx, CO_2 and SOx while increase in HC with TiO_2 dose	ASTM D-4052 D-445 D-240 D-92 D-613
C. Jegadheesan et al. [61]	2022	Ethanol	Moringa Seed oil biodiesel	5.4 kW single cylinder VCR, CI engine	Improves brake thermal efficiency by 16.54% and reduces the emission.	ASTM D6751, ASTM D4629
S. K. Kurre et al. [62]	2021	Ethanol	Diesel fuel	5.2 kW, Single Cylinder 4-stroke CI engine	Viscosity decrease 20% after 100 run. Total acid number (TAN) increases upto 63% over the period of time which restricts the use of pure ethanol as fuel.	SVM3000, ASTMD445

Table 1.6– Tribological behaviour of additives/nanoparticles							
Article Citation	**Year**	**Additives / Nano particles**	**Base Fuel**	**Engine/ instrum ent**	**Tribological Behaviour**	**Stand ards**	**Ref.**
Saravana n et al. (2020)	2020	Ethanol	Ethanol-fueled diesel engine	Single Cylinder 4-stroke CI engine	Ceramic coating was used on cylinder head, piston, and valves to resist the wear by plama spray coating method assisted with 0.5 mm thick zirconia. Heat energy carried out by Cooling media was decreased.	ASTM D675 1	[51]
Arunpras ad et al. (2022)	2022	La2O3 nanoparti cles	Algae biodies el	Diesel engine, four ball tribo meter	B20 exhibited a notably elevated friction coefficient when subjected to a stable 40 kg load with runtime, in contrast to blends containing La2O3. As the quantity of La2O3 in B20 increased, there was a concurrent reduction in both wear and friction.	ASTM 4172, D445, D129 8	[54]
Dey et al. (2021)	2021	cerium oxide (CeO2) Nanoparti cles	Palm biodies el	3.5 kW, Single Cylinder 4-stroke CI engine, Pin ball meter	The wear rate of lubricants contaminated with nanofuels has been observed to be lower than that of lubricants contaminated with diesel under varying speed and load conditions, with reductions of 7.94%, 30%, and 28.06% at varying speeds, and 7.94%, 30.33%, and 17.04% under varying loads, respectively.	ASTM D445, D129 8,D61 3, D240	[55] , [56]
Loo et al. (2023)	2023	magnesiu m oxide (MgO), graphene (G), aluminiu m oxide (Al2O3) Nanoparti cles	filtered tire pyrolysi s oil (FTPO) and biodies el-diesel blend (B20)	NA	Low concentration of the addition of nano particles shows best anti-friction performance. Al2O3 reduces 22.09% wear.	ASTM 4172, D445, D129 8	[56]
Larsson et al. (2022)	2022	Boric acid fuel additive	ethanol (E85), gasoline , diesel and marine gas oil (MGO)	Recipro cating sliding ball-on-disc setup	Experiments conducted using Marine Gas Oil (MGO) or diesel fuel show the lowest levels of friction and wear, while gasoline exhibits slightly higher levels, and E85 demonstrates the highest. The appearance of the worn surfaces, and consequently, the tribofilms that develop, differ depending on the type of fuel used.	ASTM D607 9	[57]
Jamshaid et al. (2022)	2022	cotton seed and palm oil	Diesel fuel	Single Cylinder 4-stroke CI engine	Improved tribological characteristics, The wear coefficient for diesel fuel was 22.8%, 25.7%, 27.9%, 29.9% and 19.9% higher than C05P15, C10P10, C15P05, COME20 and POME20, respectively.	ASTM D423 9, ASTM D675 1	[58]

Milano et al. (2022)	2022	Waste cooking oil biodiesel, Calophyllum inophyllum	Diesel fuel	four ball tribometer	The incorporation of WC biodiesel, W70CI30 biodiesel, and a blend of W70CI30 biodiesel with diesel into the lubricant has led to a notable enhancement in the Coefficient of Friction (CoF) and a reduction in Wear Scar Diameter (WSD).	ASTM D6751	[59]

The comprehensive overview of studies examining the impact of additives and nanoparticles on CI engine performance, emissions, and tribological behaviour. In Table-1.5, various additives such as antioxidants, glycerol ethoxylate, and ethanol, along with nanoparticles like Bi2O3 and Al2O3, were tested with different base fuels in CI engines. These additives and nanoparticles demonstrated improvements in combustion efficiency, reduced emissions of NOx, HC, CO, and smoke, and enhanced ignition behaviour. Table-5 focuses on the tribological behaviour of additives and nanoparticles, including La2O3, cerium oxide (CeO2), and magnesium oxide (MgO), when used with different base fuels in CI engines and tribometer tests. These studies highlight reductions in wear and friction with the incorporation of nanoparticles and additives into the lubricants, underscoring their potential to enhance engine durability and efficiency. Together, these tables showcase the diverse range of additives and nanoparticles being explored to optimize CI engine performance, emissions, and wear characteristics.

Conclusion

In conclusion, the extensive body of research presented in this study highlights the remarkable potential of algae-ethanol fuel blends for compression ignition (CI) engines. These alternative fuels, derived from algae-based biofuels and enhanced with ethanol, have shown significant promise in improving engine performance, combustion characteristics, and environmental sustainability. The key takeaways from this review can be summarized as follows:

- These blends enhance engine performance, leading to greater energy efficiency and fuel economy. The studies demonstrate that algae-ethanol fuels significantly reduce harmful emissions, including nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). These reductions contribute to a cleaner and more environmentally friendly combustion process.
- The use of optimization techniques such as response surface methodology (RSM), Taguchi method, and artificial neural networks (ANN) has proven effective in fine-tuning engine parameters and fuel formulations, enabling researchers to maximize performance while minimizing emissions.
- The incorporation of nanoparticles, such as CeO2 and Al2O3, into algae-ethanol biodiesel blends has demonstrated enhanced engine performance and reduced emissions, further improving the environmental footprint of these fuels.
- Life cycle analysis (LCA) studies emphasize the reduced environmental impact of algae-ethanol fuels compared to petroleum-based counterparts, offering prominent benefits, including reduced BTE, CO, HC, and NOx emissions.

Taking in to account of these findings, it is evident that algae-ethanol fuel blends hold great promise for revolutionizing CI engine technology. Continued research and development efforts in this domain are crucial to further refine these alternative fuels, optimize their performance, and facilitate their broader adoption in the automotive sector. The integration of advanced materials, optimization techniques, and sustainable practices will undoubtedly play a pivotal role in shaping the future of transportation towards greater efficiency and reduced environmental impact.

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.

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