GAU Research Journal **49** (1) : 72-101 (January 2024)

Sustainable Fuel Alternatives: The Impact of Algae-Ethanol Blends on Engine Dynamics and Emissions.

KALPESH VAGHELA and SANJAY PATEL*

*A. D. Patel Institute of Technology, CVM University, Anand (India).

ABSTRACT

This vast assessment investigates the escalate field concerning algae-ethane gasoline brews for squeezed ignition (CI) engines, providing a thorough examination of the research conduct in this sector. Include ethane into algae-based concoctions enhances their performance, combustion traits, and emissions profiles. The cumulative findings underscore the significant influencer of algae-ethane gases on both engine performance and emissions reduction. Mixing algae-set biofuels with ethane and diesel consistently yields positive outcomes across various engine types. Remarkably, the B20 blend—consisting of 20% ethane and 80% diesel—demonstrates improved brake thermal efficiency (BTE) and reduced emissions of nitrogen oxides (NOx), carbon Monoxide (CO), hydrocarbons (HC), and particular matter (PM). Numerous optimization techniques, including response surface methodology (RSM), Taguchi mechanism, and artificial neural networks (ANN), have proven efficient in finely tuning engine parameters to optimal efficiency and minimize emissions. Additives such as glycerol ethoxylate (GE), butylated hydroxytoluene (BHT), and n-pentanol have also been researched to enhance ignition and combustion characteristics. Life cycle analysis studies have highlighted the environmental advantages of algae-ethane gases, demonstrating reduced environmental impact compare to petroleum-based gases. Biodiesel deriving from algae exhibits the potential to improve BTE by up to 5%, alongside significant reductions in CO, HC, and NOx emissions. Additionally, the inclusion of nanoparticles such as CeO2 and Al2O3 shows promise in enhancing engine performance and reducing emissions when incorporating in algae-ethane concoctions.

Keywords : Algae biofuel, ethanol, optimization, brake thermal efficiency (BTE), emissions reduction.

INTRODUCTION

The pursuit of ecological sustainable and environmentally irresponsible energy resources has roused heightened excitement for biofuels while originating from renewable resources. In this spectrum, microalgaes have commended considerable interest due to the elevated lipid concentrations, fast growth kinetics, and ability to alleviate carbon emissions through sequestration of carbons dioxide (CO2)[1]–[4].

This comprehensive studies includes advancements and investigations within the domain of biofuels derived out of microalgaes, embracing inspections of their combustion behaviour, ecological

implications, and prospective trajectories. The use of microalgaes is a source of biofuels have been a subject of extensive investigations over the past few years. Researchers explored various aspect of algae-based biofuels, ranging from the assessment of combustion characteristics in internal combustion engines to evaluate of the potential in to reducing greenhouse gas emissions. This review integrates, findings from a range of studies to provide a Hulk perspective on the current state of knowledge in the field of algae biofuel and ethanol. In line with that, NITI Aayog and Ministry of Petroleum & Natural Gas have published report in June 2021 showcasing the roadmap for making 25% ethanol blending by 2025 and much emphasis on development of flex-fuel technology [5].

The combust performance of algae-based biofuels in various engine types have been key foci of research efforts. Several study has examined the use of algae oil and algaes biodiesel as fuel alternatives into internal combust engines and concluded that algal oil and algae biodiesel has slightly higher brake thermal efficiency and lower NOx emission comparatively.[1], [6], [7].

Saraswat and Chauhan (2020) are determine that a energy densities of algae biofuel was approximately 5–8% lower when compares to petrol and diesel. The findings indicated that, through all blending rations, the brake-specific fuel consumption (BSFC) of butanol and algae oil blend is higher than the pure petrol under all operating condition. This primarily attributed to the lower calorific values of butanol and the algae oil when compared to petrol. Data also reveals similar properties between the 5%, 10%, and 15% butanol-algae blends and petrol. Found that algae biodiesels exhibits promising combustion stability and emission performance in the CI engines, with significantly reduction in particulate matter emission [6]. Furthermore, the impact age of blending algae-based biofuels with a other conventional fuel, like ethanol and diesels, has been explored wildly. Studies have being investigated the effects of fuel blends on engine performances and emission. They determined the BTE increased using blends upto 5% and BSFC was decreased uto 10% [8]–[10]. Rao et al. (2021) demonstrated that the addition of ethanol to Niger-Diesel blend at varying injection pressure resulted in improving engine performance and reduced emission of nitrogen oxidizes. Their resulting indicated that up to the 200 bar injection pressure, engine produced high brake power more and beyond it performance deteriorates [9]. High ethanol levels resulted in intensified combustion and reduces combustion stability, evident from cyclic variations. Especially, when ethanol content reaches 30%, there was substantial increments in the coefficient of variation of peak pressure (COVpmax). While increasing ethanol content, soot emissions exhibited a notable reductionness ranging from 11.28% to 47.23%. However, this reduce was accompanied by an increase in NOx emission ranging 2.68% to 7.04%, as well as HC emissions up position rising by 9.99% to 21.47%. The studying recommended that ethanol blending ratios should not surpass 30% [11]. This evaluation also covers the effects of additives/nano-particles on performance of CI engines. Firew et al. (2022) revealed the introduction of NiZnFe2O4 nanoparticles into the ethanol-diesel emulsion decreased BSFC by 27.86% while simultaneous enhancing brake powers by 7.74% and brake torques by 3.53%. [12].

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

In addition to performance considerations, these review addresses the environment impact of algae biofuels. Algae cultivations presents an opportunity to utilizes high-purity carbons dioxide sources, contributing carbon captures and reduce net greenhouse gas emissions.in the comprehensive review of Current Strategy's and Prospects on Algae for Remediation and Biofuels by Kandasamy et al. (2021) discussing the advantages of algae cultivations like waste water treatments, CO_2 absorption et cetera. They revealed the demeritary like fuel production costing can be reduce by development more efficient technology. [14] Ou *et al*. (2021) outlining the opportunities and challenge of using high-purity CO_2 for algae cultivating and biofueling production in United State [15]. Microalgae holds the capacity to generate ranges of biofuels, such as the biodiesel, bioethanol, and biomethane. Additionally, microalgae can be served as to means to captures carbon dioxide (CO_2) from the atmosphere. The cultivating of microalgae holds promise satisfying approximately 20% of the world's demands for transportation fuel. Moreover, it has potentials sequestering as much as 10% of CO2 emissions worldwide [16].

So, like, the use about low-lipid waste algae for the energy production offering kind of a sustainable way to waste management. Kowthaman and Selvan (2020) did an - kinetic study on the using low-lipid waste algae for the energy development, where they highlighted much it's potentially as a green fuel source. Low-lipids waste algae maybe can serve just as a raw material to produce biofuels using that pyrolysis thing. The activation energy needed for the pyrolysis of this waste algae is usually low, and somewhere in the range from 8.7 to 20.9 kJ/mol, meaning the process can be started easily. To Paralyze those low-lipid waste algae might be done at rather modest temperatures, typically staying in the range of like 300 to 500°C creating it more of an energy-efficient way then other kinds of biofuel production. [3] Evaluations and life cycle assessments plus cost analysations have been conducting to assess the environmentally and economic viability for those algae-based biofuels. That algal biofuels examined in there research had a varying price span from around $3.39 to about $5.93 per a gasoline gallon equivalent, depending on whichever conversion route was chose. And in terms of greenhouse gases (GHG), the algal biofuels showed a significant advantage over regular gasoline with emissions might ranging from 0.0185 to 0.0383 kg CO_2-eq per every MJ of fuel [2][17]. Bui et all (2022) did a life-cycle cost analysis of innovative marine dual-fuel engines under, uncertainties, providing insights about the economic aspects for adopting those alternative fuels they concluded that a dual fuel engine may be much cost effective [17].

This paper will explore future prospects & challenges with the widespread adoption of algae-based biofuels. It potentially provides insights around the strategies to optimise microalgae cultivation as well as the developed advanced conversion technologies. Plus, it's also discusses the role from algae-based biofuels to address

climate change and enhancing energy security. By looking at the combustion's performance, environmental impact, and futures prospects of the biofuels, this review aiming to provide a comprehensive resource to researchers, policymakers plus stake holders who is interested in this field of renewable energy.

METHODOLOGY

This study is motivated by examining of the newest advancements and possible obstacles regarding the using of algae-ethanol blend biofuels on compression ignition (C-I) engines. In order to understand comprehensively the present, advancements and pending hurdles, there was a deep analysis kind of into contemporary literatures which was done as a main source of info. The Preferred Reporting Items for Systematic Reviews & Meta-Analyses, a well-known and acknowledge protocol for performing systematic reviews of literature were employed this investigation.

This methodology uses meticulously structured approaches that's selected to trying to reduce biases, therefore ensuring acquiring precise information, culminating in formulating conclusions that are dependable credible [18].

Approach to Conducting Literature Search

Investigations now been conducting using a Science Direct data bank, Plus, some other resources were added. Especially, Those were databases having good respect for their credibility, even the completeness, also they cover more than thousands of 5200 publication in the energy areas, in addition to more than 450 texts early related to renewable energies sources considering environmental sustainability. A search string were Device, it leverage our expertise in relevant field, The particular way of search string is explaining 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	63

Research review process involves systematic refining to gather relevant articles in algae-derived biofuels blend with ethanol for compression ignite engines. The Initial phase encompasses a broad exploration using search string "Algae fuel, Ethanol blend" Employing Boolean operators "AN" and "OR," we retrieve an extensive result of 42,249 records. Subsequently search is narrow by focusing for the desired timeframe (2014-2024,) maintaining the same search string and Boolean operators. Time frame considered chosen to studies research conducting about algae fuel and ethanol blend comprehensiveness. This step yielded 20,192 results. To enhanced scholarly

creditability, we limit the search to journal publication, persisting in search string "Algae fuel, Ethanol blend and same boolean operator. This process reduce outcomes to 2,054 articles. Further refining our selecting, we consider articles shows impact factors greater than 2, maintaining a consistent search string and Boolean operator. This filtrate lead to subset of 679 relevant articles.

Ensuring our restrictions of accessibilities we concentrate solely on open access publications using same search strings and Boolean operators ultimately identify 63 suitable articles. A database with articles which containing titles abstracts and full texts is create in Mendeley reference management software, This meticulous and progressively focusing approach Results in refined collection ensuring scholarly value, recency relevance, and availability for research work on algae-ethanol blend biofuels for compression ignite engines for the best of better understanding the research.

Inclusion/exclusion criteria

The critical studies focus on investigating recent progresses and upcoming challenge of the utilization of algae-ethanol blend biofuels for CI (Compression Ignition) engines. The study be employing a wide search strategy for identifying articles that meets specific include criteria. The search process was meticulous designed for ensuring the selection of relevant articles and high-quality. Inclusion criteria for articles selections encompassed key aspect. Firstly, articles needed directly addresses the topic algae-derived biofuel blend with ethanol for I.C. engines, ensuring research's alignments with central themes of study. Secondarily, the publication years limited to the range 2014-2024 enabling the incorporation recent advancement in the field. This choice ensure that review capture most up-to-date insight and finding.

We ensure credibility of the choosing articles only peer-reviewed journal publication are considered..! Moreover, Open Access articles was prioritized to enhance accessibility promoting availability of research findings to wider audience. The scope of review encompassed various research aspect, Including performance evaluations, combustion characteristic, emission analysis, feasibility assessment, and related topic concerning applications Algae-ethanol blends in CI engines. This ensure comprehensive coverages of subjects matters, incorporating experimental investigation, theoretical analyses, AND reviews to provide a holistic understanding of topics.

Key emphasis of the include criteria was the direct relevance to CI Engines and Effect of Fuel performance on engines. This REQUIRED that selected articles specifically addressed utilizations algae-ethanol blends for biofuel in CI engines.

Exclusion Criteria:

1. Irrelevant Topics: Articles what do not exactly address an utilization of algae-ethanol mixtures as biofuel for Compression Ignition engines were excluded from the considerations.
2. Publication Year: Articles, the published before 2014 or after 2024, were all excluded to focused recent developments! Inside the specified timeframes. Only one article was chosen to ensure a method study from the year was 2003,
3. Publication Type, Non-peer-reviewed sources involving conference shows, and workshop recitations were excluded to uphold standard credible rigorous researches,

4. Inaccessible Content : articles, that was not open access Or not readily available for through review.. Were excluded due to some limitations, in accessibility.
5. Lack of Relevance : Articles that not provide lots on Insights into performance combustion characteristics emissions analysis feasibility assessment or others pertinent aspects of algae-ethanol blends in CI engine were excluded from review.
6. Poor Methodology: Articles having lack of sound research methodologies experimental designs or grounded data analysis which potentially compromise findings reliability were excluded to ensure overall quality of selected literature.

By applying this criteria of exclusions, the Review process aim to ensure the careful selections of article shown in Figure 2.1 aligned the Study's scope, maintain objectivity academic, and contribute meaningfully to synthesis research outcomes in field of algae-ethanol blend biofuels for compression ignition engines.

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.

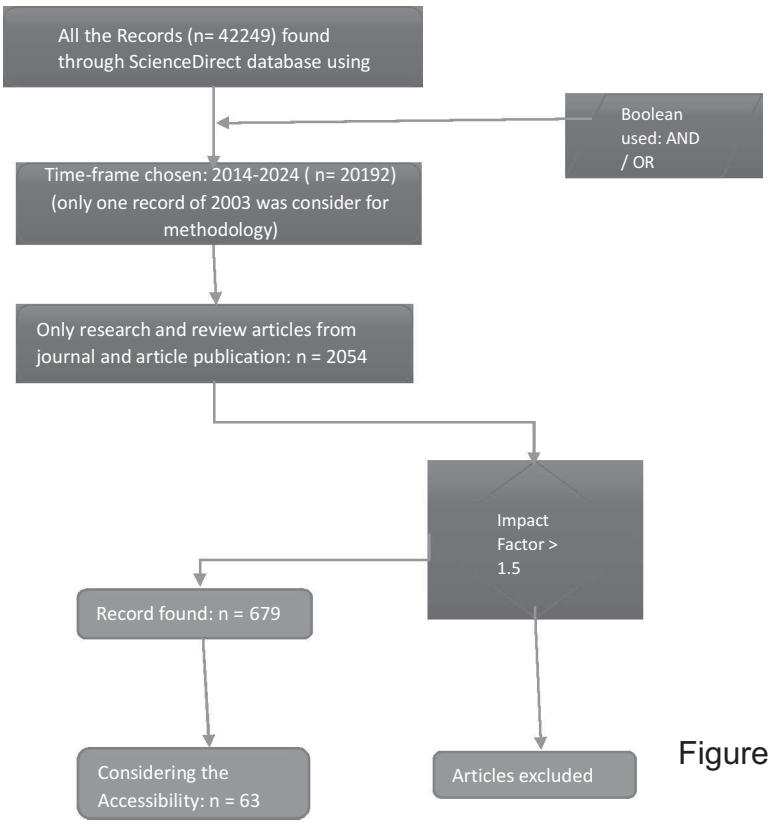


Figure 2.1 : Process chart for selection

RESULTS

Algae-Based Biodiesel Performance and Emissions in CI Engines

Algae-based biodiesel offers a promising alternative fuel derived from renewable resources. It shares many characteristics with traditional petroleum diesel and can be used in existing diesel engines without modifications. This type of biodiesel can reduce emissions of harmful pollutants like carbon monoxide, hydrocarbons, and particulate matter, although it may increase nitrogen oxide emissions. The emissions and performance of algae-based biodiesel depend on several factors, including the specific algae species, production methods, and the blend ratio with petroleum diesel.

Adeniyi et al. (2018) discuss the current state and future prospects of algae biofuel, highlighting several key challenges that need to be addressed to make algae-derived biodiesel economically viable. These challenges include reducing production costs, increasing algae oil yields, creating efficient and scalable production processes, and developing cultivation methods that do not compete with food production, as shown in figure 3.1. Despite these hurdles, the authors argue that algae-based biodiesel can significantly contribute to reducing greenhouse gas emissions and improving air quality. The paper provides evidence that algae-based biodiesel can lower emissions of pollutants such as carbon monoxide, hydrocarbons, and particulate matter. Additionally, the ability of algae to grow in various environments, including wastewater, emphasizes its sustainability as a biodiesel source. The authors conclude that algae-based biodiesel is a promising, sustainable, and environmentally friendly alternative to petroleum diesel [19].

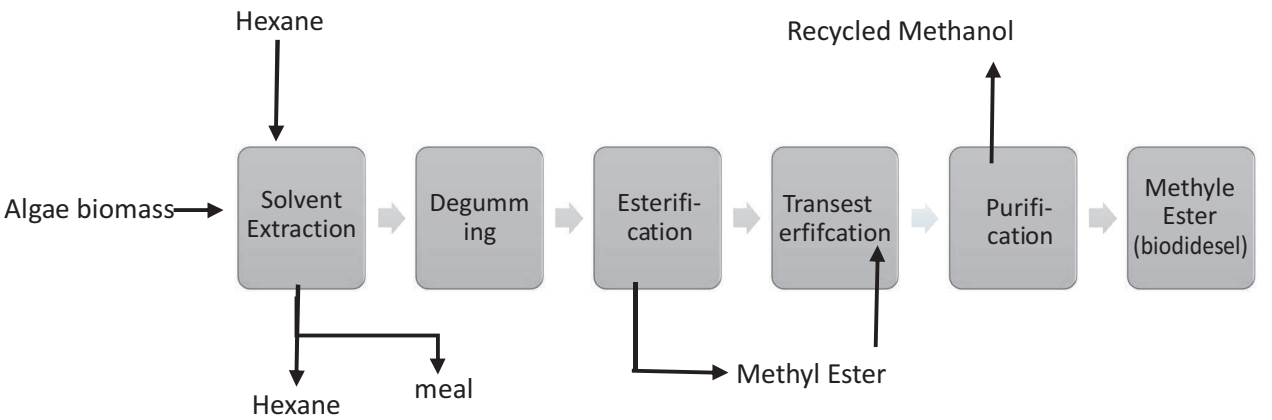


Figure 3.1 : Conventional transesterification process [19]

Karthikeyan et al. (2020a, 2020b) examined the emission and performance of a CI engine using S. Marginatum macroalgae biofuel blends. These blends were compared to ASTM D6751 standards, and engine tests were conducted at a constant 1500 rpm under various load conditions. The B20 blend showed enhanced combustion efficiency, especially at high and partial loads, and reduced exhaust emissions (excluding NOx) by up to 20%, particularly at high loads. However, the 20% SMME blend increased NOx emissions despite improving thermal efficiency [20,21] .

Kumar et al. (2021) utilized an adaptive neuro-fuzzy inference system (ANFIS) and response surface methodology (RSM) to produce biodiesel from jatropha–algae oil and examine its performance and emissions in a diesel engine-generator setup. The study employed transesterification for biodiesel production and used RSM and ANFIS to predict yield. Results showed that while diesel had the lowest brake specific fuel consumption (BSFC), the B20 blend had similar results with good brake thermal efficiency (BTE). Jatropha-algae biodiesel blends reduced hydrocarbon (HC) and carbon monoxide (CO) emissions, though they slightly increased nitrogen oxide (NOx) emissions compared to pure diesel. Overall, the blends demonstrated favorable performance and emission characteristics [22].

Saputra Nursal et al. (2021) performed a comparative study on the autoignition characteristics and emissions of biodiesel derived from palm oil, waste cooking oil, tyre pyrolysis oil, algae, and jatropha. The study concentrated on algae-derived biodiesel from Botryococcus braunii (B. braunii), a microalgae species prominent for producing up to 65% of its dry weight as hydrocarbons, particularly triterpenes. B. braunii's high content of hydrocarbons, ether lipids, saturated and mono-unsaturated fatty acids, and triacylglycerols makes it ideal for biodiesel production. The ignition delay for algae biofuel at 2 vol% concentration was recorded at 1.22 ms, which is longer than other sources. Higher injection pressures and ambient temperatures reduced ignition delays, affecting combustion quality by increasing fuel molecular size and weakening C-H bonds. The study concluded that algae biodiesel had the lowest autoignition temperature and emitted the least carbon monoxide and hydrocarbons among the biodiesel sources studied [23].

Rui Shi et al. (2018) conducted a life cycle assessment (LCA) of four pioneering algae harvesting methods and two new algae oil extraction techniques to evaluate their environmental impacts from algae cultivation to renewable diesel production. The LCA revealed that these technologies could significantly reduce greenhouse gas emissions compared to conventional methods, with acoustic harvesting and wet extraction showing the most promise. Acoustic harvesting uses sound waves to induce algae cell flocculation, easing water separation, while wet extraction uses a solvent to extract oil from algae biomass. These innovations have substantial sustainability potential, but further research is needed to optimize and reduce their environmental impact. The LCA considered factors such as greenhouse gas emissions, water and land use, energy consumption, and air and waterborne emissions. Acoustic harvesting could reduce greenhouse gas emissions by up to 40%, and wet extraction by up to 25%, compared to conventional methods as shown in figure 3.2 [24].

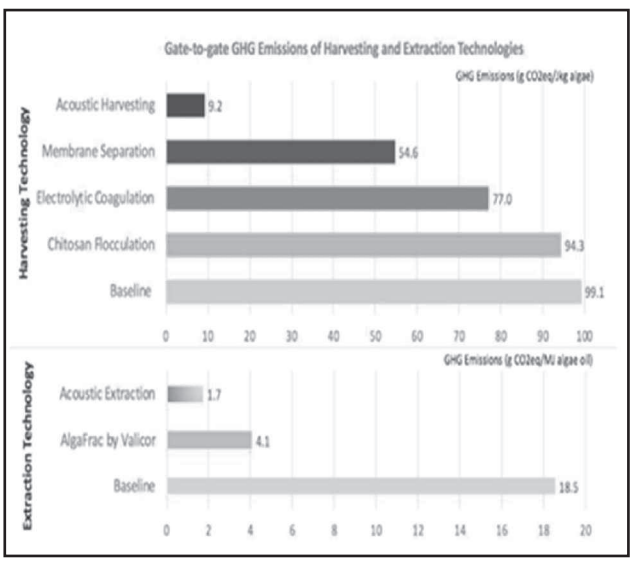


Figure 3.2 Comparison of harvesting and extraction technologies [19]

S. Pavuluri et al. (2020) examined the effects of ethanol-biodiesel blends on the performance, combustion, and exhaust characteristics of a compression ignition (CI) diesel engine at various compression ratios. Although this study was not directly focused on algae biofuel, algae could serve as a feedstock for such blends. The blends used were E10 (10% ethanol and 90% biodiesel), E20, E30, and E40 (40% ethanol and 60% biodiesel). Results revealed that ethanol-biodiesel blends enhanced the engine's brake thermal efficiency (BTE), especially at higher compression ratios, with a 2.5% increase in BTE for E10 at a 17.5:1 compression ratio and a 4.5% increase for E40 at a 19.5:1 compression ratio. These blends also reduced emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), although nitrogen oxides (NOx) emissions increased. The study suggests that ethanol-biodiesel blends are capable for enhancing CI diesel engine performance while reducing emissions [25]. M. Ranjithkumar et al. evaluated the performance and emissions of a single-cylinder, four-stroke direct injection diesel engine using blends of Calophyllum Inophyllum methyl ester (CIME), microalgae methyl ester (MAME), and diethyl ether (DEE) as alternative fuels. The fuel mixtures included 20% CIME, 40% MAME, and 60% DEE by volume. The B40 blend (40% CIME, 40% MAME, and 20% DEE) exhibited the best performance, with the highest brake thermal efficiency (30.89%), lowest specific fuel consumption (222.06 g/kWh), and minimal smoke opacity (2.16%). This blend also reduced CO emissions to 0.26% and NOx emissions to 46.26 ppm compared to conventional diesel. Adding DEE improved the volatility and compatibility of the blends with diesel, enhancing atomization and combustion. The B40 blend also had a shorter ignition delay and longer combustion duration than diesel, leading to lower emissions of HC and CO [26]. Saravanan et al. (2020) studied the effects of antioxidants, specifically butylated hydroxytoluene (BHT) and tert-butyl hydroquinone (TBHQ), on the performance and emissions of a CI engine running on algae-derived biodiesel blends. These blends consisted of 20% algae biodiesel and 80% conventional diesel. The results revealed that antioxidants improved the oxidative stability of the blends and reduced NOx and smoke emissions. Optimal NOx reduction was attained with 200 ppm of BHT and 100 ppm of TBHQ. The addition of antioxidants also positively impacted the brake thermal efficiency of the CI engine, highlighting the benefits of using antioxidants in algae biodiesel blends for better combustion efficiency and lower emissions [27].

Medhat Elkelawy et al. (2021) studied the performance and emissions of a single-cylinder, four-stroke DI diesel engine using blends of algae biodiesel, diesel, and n-pentane in varying ratios (20%, 40%, 60%, 80%). The B40 blend (40% algae biodiesel, 40% diesel, 20% n-pentane) revealed the best results, achieving the highest brake thermal efficiency (30.89%), lowest specific fuel consumption (222.06 g/kWh), and minimal smoke opacity (2.16%). This blend also reduced emissions of CO (0.26%) and NOx (46.26 ppm) compared to pure diesel. The study highlighted the renewable nature of algae biodiesel and the combustion-enhancing properties of n-pentane, emphasizing the importance of optimal blend ratios for improved engine performance and emissions [28]. ElFar et al. (2021) reviewed the potential of algae as a bioenergy source and the role of Industry 5.0 innovations in improving algae biofuel production. They discussed using artificial intelligence to

optimize cultivation, robotics for harvesting, and big data for monitoring growth[29]. Wang et al. (2023) highlighted the promise of algae for biofuels and bio-products due to their rapid growth, adaptability, and low ecological impact. Despite challenges such as high production costs and low yields, ongoing research aims to overcome these barriers, with expectations that algae-based biofuels will become more competitive with conventional energy sources[30]. Shivendra et al. (2021) showed that integrating algae biodiesel into CI engines significantly enhances brake thermal efficiency (up to 4.5% with an 80% blend) and reduces emissions of HC, CO, and PM by up to 25%, 40%, and 50%, respectively. However, NOx emissions tend to increase with higher biodiesel content [31].

Suresh Vellaiyan (2024) blended an aqueous ammonia emulsion and a zinc sulfide/copper (ZnS/Cu) nanocomposite with an algae biodiesel-diesel blend to identify optimal parameter levels for enhanced performance and reduced emissions. Algae were cultivated alongside wastewater treatment, and the properties of the biodiesel and the nanocomposite's structural and surface morphology were analyzed. Using response surface methodology for optimization and conducting confirmation tests, the study found that algae cultivation effectively removed wastewater nutrients. The optimal process parameters were determined to be 10% biodiesel, 14% aqueous ammonia, and 95 ppm of ZnS/Cu [63].

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). Particularly, 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 hydroxyl-toluene (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).

Article Citation	Year	Engine Used	Type of Algae /blend Used	Engine Parameters considered	Key Finding
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.

Article Citation	Year	Engine Used	Type of Algae /blend Used	Engine Parameters considered	Key Finding
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 hydroxyl-toluene 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.

Effect of added ethanol on performance and emission of CI engine

Ethanol-diesel blends have potential for improving the performance and emissions of compression ignition (CI) engines. This review explores the impact of adding ethanol to diesel fuel, particularly in biodiesel blends, on CI engine performance, combustion characteristics, and emissions. Munsin et al. (2015) studied glycerol ethoxylate (GE) as an ignition improver in hydrous ethanol (EtOH) under CI conditions. GE reduced the EtOH injection rate by 10%, increased injection delay and duration, reduced ignition delay, and decreased premixed burn heat release. Soot emissions dropped by 15% with 5% GE[32]. Taghizadeh-Alisaraei and Rezaei-Asl (2016) evaluated ethanol addition to diesel in a six-cylinder CI engine. A 6% ethanol blend (D94E6) improved torque and power by 3.8% but increased engine block vibration, causing higher RMS and kurtosis values. Exceeding 8% ethanol prolonged ignition delay, leading to combustion irregularities and knocking [33]. Rossomando et al. (2017) used computational fluid dynamics (CFD) simulations to assess ethanol concentration and ignition improvers on CI engine performance and emissions. A B20 blend (20% ethanol, 80% diesel) improved brake thermal efficiency (BTE) by 2.5% and

reduced NOx and particulate matter (PM) emissions by 15% and 25%, respectively [34]. Nour et al. (2019) investigated ternary blends of pentanol/hydrous ethanol/diesel (Pe10E10D80) and octanol/hydrous ethanol/diesel (Oc10E10D80) in a CI engine. These blends revealed lower peak cylinder pressures and altered heat release rates. The Pe10E10D80 blend increased BTE by 2.5% and reduced NOx, PM, and smoke emissions by 15%, 25%, and 30%, respectively [35]. Kulanthaivel et al. (2021) investigated various ethanol and algae biodiesel blends. The blend with 15% ethanol and 5% algae biodiesel improved fuel efficiency by 10.2% compared to diesel. The blend with 10% ethanol and 10% algae biodiesel had the lowest emissions, reducing NOx by 19.7% and CO by 9.7%. Additionally, the 15% ethanol and 5% algae biodiesel blend enhanced combustion stability by 19.2% and reduced knocking by 10.7% [36].

The "Roadmap for Ethanol Blending in India 2020-25," released by NITI Aayog and the Ministry of Petroleum & Natural Gas, aims to significantly increase ethanol-blended gasoline usage. Key objectives include nearly doubling ethanol production capacity by 2025-26, ensuring nationwide availability of E10 fuel (10% ethanol) by April 2022, and gradually introducing E20 fuel (20% ethanol) from April 2023, aiming for full coverage by 2025. Additionally, vehicles compatible with E10 blends will be available by April 2023, followed by E20-compatible vehicles in 2025. These efforts aim to enhance energy security, boost renewable fuel use, and reduce emissions in India [5].

John et al. (2022) reviewed exhaust emissions from CI engines using ethanol as an alternative fuel. They concluded that ethanol's impact on emissions varies based on ethanol concentration, engine conditions, and fuel injection systems. Lower ethanol concentrations in ethanol-diesel blends reduce CO, HC, and PM emissions but increase NOx emissions. Higher ethanol concentrations lower NOx emissions but increase CO, HC, and PM emissions [37]. Liang et al. (2022) studied ethanol/diesel co-solvent blends in a CRDI heavy diesel engine. Adding 10% tetrahydrofuran (THF) to a diesel-ethanol blend (B90) improved indicated thermal efficiency (ITE) by 1.5% and reduced CO, HC, and PM emissions by 10%, 20%, and 30%, respectively. Adding 10% n-pentanol increased ITE by 1% and reduced CO, HC, and PM emissions by 5%, 10%, and 20%. Adding 10% biodiesel increased ITE by 0.5% and reduced CO, HC, and PM emissions by 3%, 5%, and 10% [38]. Beatrice et al. (2020) assessed low carbon ethanol fuel in a light-duty dual-fuel CI engine, finding that ethanol reduced PM emissions, especially in advanced combustion phases. However, at higher loads, PM emissions slightly increased (0.03 to 0.25 g/kWh) without exhaust gas recirculation (EGR). Overall, ethanol consistently lowered PM and CO2 emissions compared to diesel but increased HC and CO emissions, a trade-off deemed acceptable due to ethanol's lower PM propensity[39]. Prasad et al. (2020) investigated degummed Pongamia oil-ethanol micro-emulsions as CI engine fuels. These micro-emulsions, made from Pongamia oil, ethanol, and a surfactant, improved engine performance and reduced emissions. Tests revealed that a 10% increase in fuel efficiency, a 20% decrease in NOx emissions, and no significant change in CO and HC emissions, highlighting their potential as eco-friendly CI engine fuels[40].

Adding ethanol to CI engines enhances performance (BMEP, BSFC) and lowers CO, HC, and PM emissions, as indicated in Table 1.3. However, it can also raise NOx emissions. To address this, researchers are

investigating several strategies to reduce NOx emissions while preserving ethanol's beneficial effects on performance and other emissions. These strategies include using additives, ternary blends, co-solvents, and low-carbon ethanol fuels.

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	EN 14214, EN 590	multi-zone combustion modeling shows that ethanol addition improves thermal efficiency and reduces carbon monoxide (CO)

Article	Year	Fuel blends used	Engine performance parameters	Emission parameters	Testing standards considered	Impact on CI engine
				increased by 1.1%		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].

Article	Year	Fuel blends used	Engine performance parameters	Emission parameters	Testing standards considered	Impact on CI engine
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].

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

Patel et al. (2016) reviewed the performance, emissions, and life cycle analysis (LCA) of biofuels for compression ignition (CI) engines. They highlighted the importance of LCA in evaluating the overall environmental impact of biofuels. Compared to petroleum-based fuels, biofuels tend to have a lower environmental footprint. Biodiesel can improve brake thermal efficiency (BTE) by up to 5% and reduce emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) by up to 50%, 30%, and 10%, respectively. Ethanol can enhance BTE by up to 3% and decrease CO and HC emissions by up to 30% and 20%, respectively [41] .

Rossomando et al. (2017) employed multi-zone combustion modeling to study the effects of diesel-ethanol blends on CI engine performance and emissions. Their phenomenological approach divided the combustion chamber into homogeneous zones to account for fuel injection, evaporation, air entrainment, combustion, and emissions formation. The model was validated with experimental data from a single-cylinder CI engine using an E20 blend (20% ethanol, 80% diesel) under various

conditions. The results demonstrated the model's accuracy in predicting the impact of diesel-ethanol blends on CI engine performance and emissions[34] .

Ganesan et al. (2020) used the Taguchi method to optimize CI engine parameters for biodiesel blends. They focused on blend ratio, compression ratio, and fuel injection timing, finding the best setup to be 30% biodiesel, 70% diesel, a compression ratio of 14, and a 20° BTDC injection timing. This configuration improved brake thermal efficiency (BTE) to 38.5%, 2.5% higher than the base engine, and reduced NOx emissions by 25% to 100 ppm[42] . Prasad et al. (2020) explored degummed Pongamia oil-ethanol microemulsions as CI engine fuels using Response Surface Methodology (RSM). They optimized the blend to 50% Pongamia oil, 50% ethanol, and 0.5% surfactant, achieving a BTE of 36%, which is 1% higher than with conventional diesel [40]. Dey et al. (2020) developed a hybrid ANN-Fuzzy approach to optimize CI engine parameters for a diesel-palm biodiesel-ethanol blend. This resulted in a BTE of 39%, a 2.5% improvement, and a 20% reduction in NOx emissions to 90 ppm[43].

Kumar *et al*. (2021) optimized biodiesel production from jatropha-algae oil using ANFIS and RSM. Ideal conditions were a 6:1 methanol to oil ratio, 60°C reaction temperature, and 60 minutes reaction time, yielding 98% biodiesel with low acidity. This biodiesel showed good performance and emissions characteristics [22]. Subramani et al. (2021) optimized injection timing and antioxidant use (BHT and PY) in a CI engine running on algae biodiesel using the Taguchi method. The best setup involved delayed injection timing, 250 ppm PY, and 500 ppm BHT, significantly reducing NOx with minimal impact 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 effects of operating parameters on a CRDi engine using Response Surface Methodology (RSM) for biofuel optimization. They used RSM to model the relationship between fuel injection parameters and engine outputs such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and smoke emissions. ANOVA confirmed the significance of these models. A multi-objective optimization identified the best fuel injection settings to minimize BSFC, HC, CO, NOx, and smoke emissions while maximizing BTE. The optimal conditions for the D+LPO blend were IP = 700 bar, PM = 20%, PT = 27°bTDC, and DT = 12°, with a prediction error below 5% in validation tests. These findings revealed that the optimal settings

can enhance CRDi engine performance and reduce emissions when using D+LPO blends [46]. Dhande et al. (2022) created an artificial neural network (ANN) to predict the performance of a spark ignition engine using waste pomegranate ethanol blends. The ANN, developed in MATLAB and trained with 70% of experimental data using the feed-forward backpropagation (FFBP) algorithm, accurately predicted engine performance and emissions based on engine speed and ethanol blend ratio as shown in figure 3.4. The introduction of ethanol increased volumetric efficiency by 25%. The study shows that the ANN model is a reliable tool for forecasting engine performance with various biofuels [47].

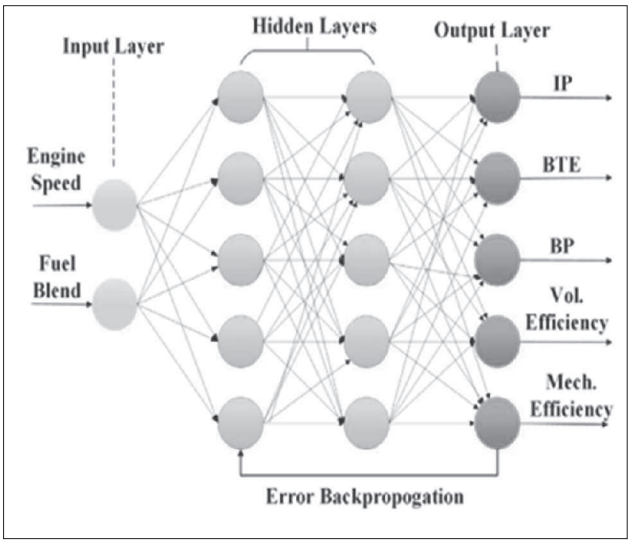


Figure 3.4 : ANN model and parameters considered [47]

P. Sharma and A. K. Sharma developed an AI-based Gene Expression Programming (GEP) model to predict the combustion performance of a compression ignition (CI) engine fueled with Waste Cooking Oil Methyl Ester (WCOME) and diesel blends. They validated the model's predictions through experimental testing of optimized operational parameters. The validation results closely aligned with the Response Surface Methodology (RSM) predictions, with all deviations within 5%. The optimal values for key operating conditions - engine load, WCOME-diesel blending ratio, fuel injection pressure, and fuel injection timing - were found to be 60.49%, 14.32%, 231.35 bar, and 23.7° before Top Dead Centre (BTDC), respectively. Under these conditions, the engine demonstrated improved performance with a Brake Thermal Efficiency (BTE) of 24.28%, a Brake Specific Fuel Consumption (BSFC) of 0.3135 kg/kWh, and a maximum pressure (P_{max}) of 58.95 bar[48]. Additionally, a fuel blend labelled D80E10C10, containing 10% ethanol, 10% castor oil, and 80% diesel fuel, was formulated for testing in a diesel engine. To predict the impact of castor oil on the characteristics of this ethanol-diesel blend, Generalized Regression Neural Networks (GRNNs) were employed, an AI algorithm suitable for small data sets. The study revealed that adding 10% castor oil improved the deficient fuel properties of the ethanol-diesel blend, keeping them within acceptable limits. Moreover, it was observed that as the engine load and compression ratio increased, brake specific fuel consumption rose while thermal efficiency decreased when using 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]

Article	Fuel used	Engine used	Optimization techniques used	Parameters considered	R2 value	Ref.
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]

Influence of additives on the biodiesel performance & tribology

Shahir et al. (2014) conducted an analysis on the viability of incorporating ethanol into diesel-biodiesel blends for compression ignition (CI) engines. Their findings suggested that optimizing biodiesel addition within the 20–25% range and adding 5% ethanol could enhance performance and efficiency when combined with conventional diesel fuel [49]. Munsin et al. (2015) investigated the use of glycerol ethoxylate as an ignition enhancer for hydrous ethanol in CI engines. Their study indicated that the introduction of ignition enhancers influenced fuel injection characteristics such as injection delay, rate, and discharge coefficient for hydrous ethanol. Compared to hydrous ethanol without enhancers (Eh95), the maximum injection rates for ethanol dedicated to heavy-duty vehicles (ED95) and hydrous ethanol with 5% glycerol ethoxylate (5%GE) were approximately 10% lower [32].

Ağbulut and Sarıdemir (2020) examined the environmental impacts of ethanol additives in spark ignition (SI) and compression ignition (CI) engines, finding significant reductions in hydrocarbon (HC) and carbon monoxide (CO) emissions by 47.9% and 47.0%, respectively, in SI engines. In CI engines, reductions were 28.5% and 25.1%. However, nitrogen oxide (NOx) emissions decreased by 2.3% in SI engines but increased by 40% in CI engines, limiting ethanol use in diesel engines [50]. Saravanan et al. (2020) explored the effects of exhaust gas recirculation (EGR) on ethanol-fueled diesel engines, noting a 2.32% and 6.32% increase in brake thermal efficiency (BTE) with 10% and 20% EGR, respectively. NOx emissions were higher at full load with ethanol but decreased with higher EGR levels [51]. Ranjithkumar et al. (2020) studied the combustion of Calophyllum Inophyllum and microalgae methyl esters with di-ethyl ether, finding a 4.4% increase in BTE and a 3.76% decrease in brake specific fuel consumption (BSFC) compared to diesel. The addition of Bi2O3 improved combustion and heat release [26], [52]. Saravanan and Krishnamoorthy (2020) found that

antioxidants in algae biodiesel reduced NOx emissions by 25% but increased CO, UBHC, and smoke emissions. Adjusting injection timing further reduced CO, UBHC, and smoke opacity by 20%, but advanced timing increased NOx emissions by 30% [27]. Dharmaprabhakaran et al. (2021) noted that adding Al2O3 nanoparticles to Botryococcus braunii biodiesel improved BTE. Similarly, Arunprasad et al. (2022) found that La2O3 nanoparticles in Naviculla Sp. biodiesel enhanced wear resistance and load-carrying capacity [53], [54]. Dey et al. (2021) and Loo et al. (2023) observed that CeO2 and Al2O3 nanoparticles in biodiesel improved BTE and reduced CO, HC, and NOx emissions, as well as wear rates [55], [56].

Larsson et al. (2022) found that boric acid as a fuel additive reduced wear in some fuels, particularly E85, by forming tribo films [57]. Jamshaid et al. (2022) recommended a B20 blend of 15% palm oil and 5% cottonseed oil biodiesel for the best BTE and tribological properties [58]. Milano et al. (2022) reported that biodiesel from waste cooking oil with lubricant reduced wear scar diameter and improved friction coefficients [59]. Liang et al. (2022) showed that adding n-pentanol and tetrahydrofuran to diesel-ethanol blends reduced HC and smoke emissions [38]. Verma et al. (2023) found that micro-algae biodiesel with butanol and TiO2 additives improved BTE and varied exhaust gas temperatures [60]. Jegadheesan et al. (2022) noted that Moringa seed oil biodiesel with ethanol improved BTE by 11.8% to 16.54% compared to diesel [61]. Kurre et al. (2021) observed that ethanol-diesel blends led to lubricating oil degradation, increasing engine wear and emissions [62].

Table 1.5 : Effect of additives on CI engine performance and emission

Article Citation	Year	Additives/ Nano particles 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

Article Citation	Year	Additives/ Nano particles Used	Base Fuel Used	Engine Used	Impact on CI Engine	Standards used
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 Bi2O3 nano Particles	Diesel fuel	Single Cylinder 4-stroke CI engine	HRR in premixed phase for Bi2O3 added blends are higher in comparison to B20 and Diesel and hence better combustion behavior. Addition of Bi2O3 nanoparticles lowers the viscosity and improves the volatility	ASTM D-4052 D-445 D-240
Dharma-prabhakaran et al.[53]	2023	Al2O3 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 TiO2 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.	ASTM D-4052 D-445 D-240 D-92 D-613

Article Citation	Year	Additives/ Nano particles Used	Base Fuel Used	Engine Used	Impact on CI Engine	Standards used
					Reductions in NOx, CO2 and SOx while increase in HC with TiO2 dose	
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/instrument	Tribological Behaviour	Standards	Ref.
Saravanan 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 D6751	[51]
Arunprasad et al. (2022)	2022	La2O3 nanoparticles	Algae biodiesel	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, D1298	[54]
Dey et al. (2021)	2021	cerium oxide (CeO2) Nanoparticles	Palm biodiesel	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, D1298 ,D613, D240	[55], [56]

Article Citation	Year	Additives/ Nano particles	Base Fuel	Engine/in strument	Tribological Behaviour	Stand ards	Ref .
Loo et al. (2023)	2023	magnesiu m oxide (MgO), graphene (G), aluminium oxide (Al2O3) Nanoparti cles	filtered tire pyrolysis oil (FTPO) and biodiesel-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, D1298	[56]
Larsso n et al. (2022)	2022	Boric acid fuel additive	ethanol (E85), gasoline, diesel and marine gas oil (MGO)	Reciproc ating 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 D6079	[57]
Jamsh aid 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 D4239 , ASTM D6751	[58]
Milano et al. (2022)	2022	Waste cooking oil biodiesel, Calophyllu m 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]

A comprehensive review of research on the impact of additives and nanoparticles on the performance, emissions, and tribological properties of CI engines is summarized. Table-1.5 assesses various additives such as antioxidants, glycerol ethoxylate, and ethanol, as well as nanoparticles like Bi2O3 and Al2O3, used with different base fuels in CI engines. These substances demonstrated improvements in combustion efficiency and reductions in NOx, HC, CO, and smoke emissions, as well as enhanced ignition behaviour. Table-1.6 explores the tribological properties of additives and nanoparticles, including La2O3, cerium oxide (CeO2), and magnesium oxide (MgO), in conjunction with various base fuels in CI engines and tribometer tests. The findings indicate that integrating nanoparticles and additives into lubricants can significantly reduce wear and friction, thereby enhancing engine durability and efficiency. Together, these tables highlight the extensive range of additives and nanoparticles being studied to optimize CI engine performance, emissions, and wear characteristics.

CONCLUSION

In conclusion, this study underscores the significant potential of algae-ethanol fuel blends for compression ignition (CI) engines. These alternative fuels, derived from algae-based biofuels and enhanced with ethanol, have demonstrated substantial improvements in engine performance, combustion characteristics, and environmental sustainability. Key findings from this review include:

- ✓ Algae-ethanol blends enhance engine performance, leading to improved energy efficiency and fuel economy. They significantly reduce harmful emissions such as nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM), contributing to cleaner and more environmentally friendly combustion.
- ✓ Optimization techniques like response surface methodology (RSM), Taguchi method, and artificial neural networks (ANN) have been effective in fine-tuning engine parameters and fuel formulations, maximizing performance and minimizing emissions.
- ✓ The addition of nanoparticles such as CeO2 and Al2O3 to algae-ethanol biodiesel blends has shown to enhance engine performance and reduce emissions, further lowering the environmental footprint of these fuels.
- ✓ Life cycle analysis (LCA) studies highlight the reduced environmental impact of algae-ethanol fuels compared to petroleum-based fuels, offering significant benefits in reducing BTE, CO, HC, and NOx emissions.

Overall, algae-ethanol fuel blends hold considerable promise for advancing CI engine technology. Ongoing research and development are essential to further refine these alternative fuels, optimize their performance, and facilitate their wider adoption in the automotive industry. Integrating advanced materials, optimization techniques, and sustainable practices will be crucial in driving 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.

REFERENCES

S. S. Satputaley, D. B. Zodpe, and N. V Deshpande, “Performance, Combustion and Exhaust Emissions Analysis of a Diesel Engine Fuelled with Algae Oil and Algae Biodiesel,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings2214-7853

K. Derose, C. Demill, R. W. Davis, and J. C. Quinn, “INTEGRATED TECHNO ECONOMIC AND LIFE CYCLE ASSESSMENT OF THE CONVERSION OF HIGH PRODUCTIVITY, LOW LIPID ALGAE TO RENEWABLE FUELS,” 2019.

C. N. Kowthaman and V. Arul Mozhi Selvan, “Waste to green fuels: Kinetic study of low lipid waste algae for energy development,” *Bioresour Technol Rep*, 11, Sep. 2020, doi: 10.1016/j.biteb.2020.100510.

S. Kesharvani and G. Dwivedi, “Algae as a feedstock for biodiesel production in Indian perspective,” in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 5873–5880. doi: 10.1016/j.matpr.2021.04.295.

R. Sarwal, India. NITI Aayog, and India.

Ministry of Petroleum & Natural Gas, *Road map for Ethanol blending in India 2020-25 : report of the expert committee.*

M. Saraswat and N. R. Chauhan, "Comparative assessment of butanol and algae oil as alternate fuel for SI engines," *Engineering Science and Technology, an International Journal*, 23(1), pp. 92–100, Feb. 2020, doi: 10.1016/j.jestch.2019.04.002.

S. Prabakaran, R. Manimaran, T. Mohanraj, and M. Ravikumar, "Performance analysis and emission characteristics of VCR diesel engine fuelled with algae biodiesel blends," in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 2784–2788. doi: 10.1016/j.matpr.2020.11.742.

A. Paul, R. Panua, and D. Debroy, "An experimental study of combustion, performance, exergy and emission characteristics of a CI engine fueled by Diesel-ethanol-biodiesel blends," *Energy*, vol. 141, pp. 839–852, Dec. 2017, doi: 10.1016/J.ENERGY.2017.09.137.

B. J. Rao, V. Srinivas, K. R. Chebattina, and P. Gandhi, "Effect of Injection Pressure on the Performance and Emission Characteristics of Niger-Diesel-Ethanol Blends in CI Engine," *Journal of Mechanical Engineering*, 18(3), 2021, doi: 10.24191/jmeche.v18i3.15415.

P. Aengchuan, A. Wiangkham, N. Klinkaew, K. Theinnoi, and E. Sukjit, "Prediction of the influence of castor oil–ethanol–dieselfi blends on single-cylinder diesel engine characteristics using generalized regression neural networks (GRNNs)," *Energy Reports*, 8, pp. 38–47, Nov. 2022, doi: 10.1016/J.EGYR.2022.10.113.

L. Geng, L. Bi, Q. Li, H. Chen, and Y. Xie, "Experimental study on spray characteristics, combustion stability, and emission performance of a CRDI diesel engine operated with biodiesel–ethanol blends," *Energy Reports*, 7, pp. 904–915, Nov. 2021, doi: 10.1016/J.EGYR.2021.01.043.

D. Firew, R. B. Nallamothu, G. Alemayehu, and R. Gopal, "Performance and emission evaluation of CI engine fueled with ethanol diesel emulsion using NiZnFe2O4 nanoparticle additive," *Heliyon*, 8(11), p. e11639, Nov. 2022, doi: 10.1016/J.HELIYON.2022.E11639.

S. Szwaja, M. Gruca, and M. Pyrc, "Investigation on ethanol-glycerol blend combustion in the internal combustion sparkignited engine. Engine performance and exhaust emissions," *Fuel Processing Technology*, vol. 226, p. 107085, Feb. 2022, doi: 10.1016/J.FUPROC.2021.107085.

S. Kandasamy, M. Narayanan, Z. He, G. Liu, and M. Ramakrishnan, "Current strategies and prospects in algae for remediation and biofuels: An overview," *Biocatalysis and Agricultural Biotechnology*, 35. Elsevier Ltd, Aug. 01, 2021. doi: 10.1016/j.bcab.2021.102045.

L. Ou, S. Banerjee, H. Xu, A. M. Coleman, and H.Cai., "Utilizing high-purity carbon dioxide sources for algae cultivation and biofuel production in the United States: Opportunities and challenges," *J Clean Prod*, 321, Oct. 2021, doi: 10.1016/j.jclepro.2021.128779.

V. Joshi, P. M. Chauhan, K. B. Joshi, and U. Resource Development Centre, "MICROALGAE CULTIVATION FOR BIOFUEL PRODUCTION AND ITS POTENTIAL TO MITIGATE CLIMATE CHANGE THROUGH CO 2 SEQUESTRATION Towards

Excellence." [Online]. Available: www.ascgujarat.org

K. Q. Bui, L. P. Perera and J. Emblemsvåg, "Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties," *J Clean Prod*, 380, p. 134847, Dec. 2022, doi: 10.1016/J.JCLEPRO.2022.134847.

D. Tranfield, D. Denyer, and P. Smart, "Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review*," 2003.

O. M. Adeniyi, U. Azimov, and A. Burluka, "Algae biofuel: Current status and future applications," *Renewable and Sustainable Energy Reviews*, 90. Elsevier Ltd, pp. 316–335, Jul. 01, 2018. doi: 10.1016/j.rser.2018.03.067.

S. Karthikeyan, M. Periyasamy, A. Prathima, and K. Sabariswaran, "Emission analysis of CI engine fueled with S. Marginatum macro algae biofuel - Diesel blends," in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3458–3463. doi: 10.1016/j.matpr.2020.05.355.

S. Karthikeyan, M. Periyasamy, A. Prathima, and K. Sabariswaran, "Performance analysis of diesel engine fueled with S. Marginatum Macro algae biofuel - Diesel blends," in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3464–3469. doi: 10.1016/j.matpr.2020.05.356.

S. Kumar, S. Jain, and H. Kumar, "Application of adaptive neuro-fuzzy inference system and response surface methodology in biodiesel synthesis from jatropha–algae oil and its performance and emission analysis on diesel engine coupled with generator," *Energy*, 226, Jul. 2021, doi: 10.1016/j.energy.2021.120428.

R. Saputra Nursal, A. Khalid, I. Shahridzuan Abdullah, N. Jaat, N. Darlis, and H. Koten, "Autoignition behavior and emission of biodiesel from palm oil, waste cooking oil, tyre pyrolysis oil, algae and jatropha," *Fuel*, 306, Dec. 2021, doi: 10.1016/j.fuel.2021.121695.

R. Shi, R. M. Handler and D. R. Shonnard, "Life Cycle Assessment of Novel Technologies for Algae Harvesting and Oil Extraction in the Renewable Diesel Pathway," 2018.

S. Pavuluri, B. Sidda Reddy, and B. Durga Prasad, "An experimental investigation on the performance, combustion and emission characteristics of CI diesel engine at various compression ratios with different ethanol-biodiesel blends," *International Journal of Advanced Science and Technology*, 29(5), 2020.

M. Ranjithkumar, S. Karuppusamy, P. Lakshmanan, D. Ragulnath, K. Saravanan, and A. M. Rameshbabu, "Study on diesel engine combustion parameters using Calophyllum Inophyllum methyl ester and micro algae methyl ester with level addition of Di-Ethyl ether," in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3388–3392. doi: 10.1016/j.matpr.2020.09.275.

S. Saravanan and N. Krishnamoorthy, "Investigation on reduction in consequences of adding antioxidants into the algae biodiesel blend as a CI engine fuel," *Fuel*,276, Sep. 2020, doi: 10.1016/j.fuel.2020.117993.

M. Elkelawy, H. Alm-Eldin Bastawissi, E. A. El Shenawy, M. Taha, H. Panchal, and K. K. Sadasivuni, "Study of performance, combustion, and emissions parameters of DI-diesel engine fueled with algae biodiesel/diesel/n-pentane blends," *Energy Conversion and Management: X*, 10, Jun. 2021, doi: 10.1016/j.ecmx.2020.

100058.

O. A. ElFar, C. K. Chang, H. Y. Leong, A. P. Peter, K. W. Chew, and P. L. Show, "Prospects of Industry 5.0 in algae: Customization of production and new advance technology for clean bioenergy generation," *Energy Conversion and Management: X*, 10, Jun. 2021, doi: 10.1016/j.ecmx.2020.100048.

X. Wang, Y. Zhang, C. Xia, A. Alqahtani, A. Sharma, and A. Pugazhendhi, "A review on optimistic biorefinery products: Biofuel and bioproducts from algae biomass," *Fuel*, 338, p. 127378, Apr. 2023, doi: 10.1016/J.FUEL.2022.127378.

K. Vaghela, S. Jha, and A. Shanmugarathinam, "An experimental approach to produce and investigate the sustainability of algae biodiesel on the performance of the single-cylinder four-stroke CI engine," *International Journal of Engineering and Techniques*,7(6), 2021, [Online]. Available: http://www.ijetjournal.org

R. Munsin, Y. Laoonual, S. Jugjai, M. Matsuki, and H. Kosaka, "Effect of glycerol ethoxylate as an ignition improver on injection and combustion characteristics of hydrous ethanol under CI engine condition," *Energy Convers Manag*, 98, pp. 282–289, Jul. 2015, doi: 10.1016/J.ENCONMAN.2015.03.116.

A. Taghizadeh-Alisaraei and A. Rezaei-Asl, "The effect of added ethanol to diesel fuel on performance, vibration, combustion and knocking of a CI engine," *Fuel*, 185, pp. 718–733, Dec. 2016, doi: 10.1016/J.FUEL.2016.08.041.

B. Rossomando, I. Arsie, and C. Pianese, "Analysis of the impact of Diesel-Ethanol fuel blends on CI engine performance and emissions via multi-zone combustion modelling," *Energy Procedia*, 126, pp. 1059–1066, Sep. 2017, doi: 10.1016/J.EGYPRO.2017.08.203.

M. Nour, A. M. A. Attia, and S. A. Nada, "Improvement of CI engine combustion and performance running on ternary blends of higher alcohol (Pentanol and Octanol)/hydrous ethanol/diesel," *Fuel*, 251, pp. 10–22, Sep. 2019, doi: 10.1016/J.FUEL.2019.04.026.

V. Kulanthaivel, A. Jayaraman, T. Rajamanickam, and S. Selvam, "Impact of diesel – Algae biodiesel- Anhydrous Ethanol blends on the performance of CI engines," *J Clean Prod*, 295, May 2021, doi: 10.1016/j.jclepro.2021.126422.

J. A. John, N. Mohammed Shahinsha, K. Singh, and R. Pant, "Review on exhaust emissions of CI engine using ethanol as an alternative fuel," *Mater Today Proc*, 69, pp. 286–290, Jan. 2022, doi: 10.1016/J.MATPR.2022.08.536.

J. Liang, Q. Zhang, Q. Ma, Z. Chen, and Z. Zheng, "Effect of various ethanol/diesel cosolvents addition on combustion and emission characteristics of a CRDI heavy diesel engine," *Energy Reports*, 8, pp. 735–748, Nov. 2022, doi: 10.1016/J.EGYR.2021.12.011.

C. Beatrice, I. Denbratt, G. Di Blasio, G. Di Luca, R. Ianniello, and M. Saccullo, "Experimental assessment on exploiting low carbon ethanol fuel in a light-duty dual-fuel compression ignition engine," *Applied Sciences (Switzerland)*, 10, no. 20, 2020, doi: 10.3390/app10207182.

S. S. Prasad, A. Singh, and S. Prasad, "Degummed Pongamia oil - Ethanol microemulsions as novel alternative CI engine fuels for remote Small Island Developing States: Preparation, characterization, engine performance

and emissions characteristics," *Renew Energy*, 150, pp. 401–411, May 2020, doi: 10.1016/J.RENENE.2019.12.150.

P. D. Patel, A. Lakdawala, S. Chourasia, and R. N. Patel, "Bio fuels for compression ignition engine: A review on engine performance, emission and life cycle analysis," *Renewable and Sustainable Energy Reviews*, 65, pp. 24–43, Nov. 2016, doi: 10.1016/J.RSER.2016.06.010.

S. Ganesan, J. Senthil Kumar, and J. Hemanandh, "Optimisation of CI engine parameter using blends of biodiesel by the Taguchi method," *International Journal of Ambient Energy*, 41(2), 2020, doi: 10.1080/01430750.2018.1456968.

S. Dey, N. M. Reang, A. Majumder, M. Deb, and P. K. Das, "A hybrid ANN-Fuzzy approach for optimization of engine operating parameters of a CI engine fueled with diesel-palm biodiesel-ethanol blend," *Energy*, 202, p. 117813, Jul. 2020, doi: 10.1016/J.ENERGY.2020.117813.

S. Subramani, K. Natarajan, and G. Lakshmi Narayana Rao, "Optimization of injection timing and anti-oxidants for multiple responses of CI engine fuelled with algae biodiesel blend," *Fuel*, 287, p. 119438, 2021, doi: https://doi.org/10.1016/j.fuel.2020.119438.

A. Ranjan, S. S. Dawn, N. Nirmala, A. Santhosh, and J. Arun, "Application of deep eutectic solvent in biodiesel reaction: RSM optimization, CI engine test, cost analysis and research dynamics," *Fuel*, 307, 2022, doi: 10.1016/j.fuel.2021.121933.

P. Saiteja and B. Ashok, "Study on interactive effects of CRDi engine operating parameters through RSM based multi-objective optimization technique for biofuel application," *Energy*, 255, p. 124499, Sep. 2022, doi: 10.1016/J.ENERGY.2022.124499.

D. Y. Dhande, C. S. Choudhari, D. P. Gaikwad, and K. B. Dahe, "Development of artificial neural network to predict the performance of spark ignition engine fuelled with waste pomegranate ethanol blends," *Information Processing in Agriculture*, May 2022, doi: 10.1016/J.INPA.2022.05.001.

P. Sharma and A. K. Sharma, "AI-Based Prognostic Modeling and Performance Optimization of CI Engine Using Biodiesel-Diesel Blends," *International Journal of Renewable Energy Research*, 11(2), 2021, doi: 10.20508/ijrer.v11i2.11854.g8191.

S. A. Shahir, H. H. Masjuki, M. A. Kalam, A. Imran, I. M. R. Fattah, and A. Sanjid, "Feasibility of diesel- biodiesel-ethanol/bioethanol blend as existing CI engine fuel: An assessment of properties, material compatibility, safety and combustion," *Renewable and Sustainable Energy Reviews*, 32, pp. 379–395, Apr. 2014, doi: 10.1016/J.RSER.2014.01.029.

Ü. Ağbulut and S. Sarıdemir, "Is the ethanol additive more environmentally friendly for a spark ignition (SI) engine or for a compression ignition (CI) enginefi," *Environ Eng Manag J*, 19(4) 2020, doi: 10.30638/eemj.2020.060.

P. Saravanan, N. M. Kumar, M. Ettappan, R. Dhanagopal, and J. Vishnupriyan, "Effect of exhaust gas re-circulation on performance, emission and combustion characteristics of ethanol-fueled diesel engine," *Case Studies in Thermal Engineering*, 20, Aug. 2020, doi: 10.1016/j.csite.2020.100643.

S. Karthikeyan, M. Periyasamy and A. Prathima, "Combustion analysis of a CI engine with Caulerpa racemosa algae

biofuel with nano additives," in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 3324-3329. doi: 10.1016/j.matpr.2020. 04.780.

T. Dharmaprabhakaran, K. Kalaimurugan, D. Somasundaram, C. Thirugnanam, H. Al Fahim, and M. Kaviyarasan, "WITHDRAWN: Performance analysis of Al2O3 nanoparticle addition with a blend of Botryococcus braunii algae biodiesel on diesel engine," *Mater Today Proc*, Feb. 2021, doi: 10.1016/j.matpr.2021. 01.346.

J. Arunprasad, R. Thirugnanasambantham, R. Rajesh, S. Sugumar, T. Jayakumar, and T. Elango, "Experimental investigation of tribological properties of Naviculla Sp. algae biodiesel with La2O3 nanoparticles," *Mater Today Proc*, 2022, doi: 10.1016/j.matpr.2021.01.792.

S. Dey, N. Moni Reang, M. Deb, and P. Kumar Das, "Experimental investigation on combustion-performance-emission characteristics of nanoparticles added biodiesel blends and tribological behavior of contaminated lubricant in a diesel engine," *Energy Convers Manag*, 244, p. 114508, Sep. 2021, doi: 10.1016/J.ENCONMAN.2021.114508.

D.L. Loo, Y. H. Teoh, H. G. How, T. Le, H. Nguyen, T. Rashid, D. Pottmaier, and F.Sher, "Effect of nanoparticles additives on tribological behaviour of advanced biofuels," *Fuel*, 334, p. 126798, Feb. 2023, doi:10.1016/J.FUEL. 2022.126798.

E. Larsson, J. Heinrichs, and S. Jacobson, "Tribological evaluation of a boric acid fuel additive in various engine fuels," *Wear*, 502–503, p. 204381, Aug. 2022, doi: 10.1016/J.WEAR.2022.204381.

M. Jamshaid, H. H. Masjuki, M. A. Kalam, N. W. M. Zulkifli, A. Arslan, and A. A. Qureshi, "Experimental investigation of performance, emissions and tribological characteristics of B20 blend from cottonseed and palm oil biodiesels," *Energy*, 239, p. 121894, Jan. 2022, doi: 10.1016/J.ENERGY.2021.121894.

J. Milano, A. H. Shamsuddin, A.S. Silitonga, A.H. Sebayang, M. A. Siregar, and H.H. Masjuki, "Tribological study on the biodiesel produced from waste cooking oil, waste cooking oil blend with Calophyllum inophyllum and its diesel blends on lubricant oil," *Energy Reports*, 8, pp. 1578–1590, Nov. 2022, doi: 10.1016/J.EGYR.2021.12.059.

S. Verma, R. Upadhyay, R. Shankar and S. P. Pandey, "Performance and emission characteristics of micro-algae biodiesel with butanol and TiO2 nano-additive over diesel engine," *Sustainable Energy Technologies and Assessments*, 55, p. 102975, Feb. 2023, doi: 10.1016/J.SETA.2022.102975.

C. Jegadheesan,P. Somasundaram, E. Devaprasanth,S. Sasikumar, L. Suriyaprasanth, A. P. Singh, and N. Jeyaprakash., "Experimental investigation on performance and emission characteristics of moringa seed oil biodiesel with added ethanol in CI engine," *Mater Today Proc*, 64, pp. 828–834, Jan. 2022, doi: 10.1016/J.MATPR.2022.05.327.

S.K. Kurre, S. Pandey, N. Khatri, S.S. Bhurat, S.K. Kumavat, S. Saxena, S. Kumar., "Study of lubricating oil degradation of ci engine fueled with diesel-ethanol blend," *Tribology in Industry*, 43, no. 2, 2021, doi: 10.24874/ti.913.06.20.11.

Suresh Vellaiyan, "Optimizing algae biodiesel blends with aqueous ammonia and nanocomposite for enhanced performance and environmental benefits", Case Studies in Chemical and Environmental Engineering, 9,2024, https://doi.org/10.1016/j.cscee.2024.10 0698.